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Mass Storage Digital Ocean Bottom Seismometer and Hydrophone (DOBSH) Controlled by Micro-processors Using ADPCM Voice Synthesizing

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Abstract

A DOBSH (Digital Ocean Bottom Seismometer and Hydrophone) and PDER (Portable Digital Event Recorder) have been newly developed. Main features are: storage of a large number of events, namely, 750 events on 4 channels, 2-minutes each and 100 Hz sampling rate; including ADPCM (Adaptive Differential Pulse Code Modulation) speech synthesis; a long (4 minutes max. on 4 channels) buffer size for the pre-event-delay using two 8 bit CMOS micro-processors. Events are identified by the event triggering algorithm. 100 Hz or 200 Hz samplings are used. On collecting data, the length of one sampling is compressed from 12 bit to 4 bit by ADPCM-IC and the compressed data are stored on digital tape. Records on the tape are synthesized by ADPCM-IC, or soft-ware on a mini-computer. By use of the ADPCM method, the total amount of data that can be put on a tape is practically increased fourfold. One cartridge tape (555-feet tape length) can store 72 MB of data when the data are synthesized. The time information is from a clock processor which can be adjusted at any time by a one minute pulse supplied from a precision clock or a 40 kHz standard time radio. Two field experiments showed the DOBSH worked correctly and proved its usefulness.

Introduction

Precise wave form is essential in recording earthquakes in order to accurately determine the earthquake foci and the nature of the seismic motion involved. In the study of natural earthquakes, the hypocenter distribution is one of the most significant aspects, which must be accurately known for the study of seismo-tectonics. Digital recording can improve the precision on wave form and dynamic range of seismic recording.

In the digital system, it is possible to obtain a 70 dB-dynamic range in wave amplitude. In direct analog recording systems, some distortions on wave form occur during the recording and playback process. Existing land-use digital event recorders, however, cannot record large numbers of earthquakes because of the limited capacity of the recording media. Presently available event recorders are limited to record less than a hundred events. To avoid the small storage capacity problem, some ocean bottom seismometers use reel-to-reel tape recorders with modifications to digital recording, but the size of the tape recorder is large and the total weight of the instrument is heavy (MOORE *et al.*, 1981, PROTHERO, 1974). Some investigators have used a mixture of event-triggering algorithm in digital form and analog recordings in which the FM method was used (BOOKBINDER *et al.*, 1978; LATHAM *et al.*, 1978). However, although the FM recording method can improve dynamic range (~40 dB) of the recording system, the total continuous recording time is not long.

In the Earthquake Research Institute, University of Tokyo, direct analog recording (DAR) has been used (HASEGAWA and NAGUMO, 1970; KASAHARA, *et al.*, 1974, 1979). The main reason for the use of DAR is the necessity to record as many events as possible in any given study. By DAR, it is not difficult to obtain one month of continuous recording. The dynamic range is, however, 30 dB at best. For example, near the Japan trench, 500 events were recorded during one month (KASAHARA *et al.*, 1982). In such a region, precision wave form must be sacrificed in order to record numerous earthquakes.

By using recent technological advances in electronics, such as highly integrated circuit (IC), 8 bit CMOS (Complementary Metal Oxide Semiconductor) micro-processors, 64 kbit CMOS RAM (Random Acess Memory) and ADPCM (Adaptive Differential Pulse Code Modulation) ICs, it is possible to build a new instrument with improvements. In addition to the above new devices, a high density (6,400 bit-per-inch (BPI)) cartridge tape has recently been developed which can be used for a back-up to a computer-disk system. The total amount of recording possible on a high-density cartridge tape is 20 MB in digital recording form, which is 20~40 times more than the previous quarter-inch digital cassette tape. KOELSCH *et al.*, (1982) have used this high density cartridge tape for an ocean bottom hydrophone.

Using these new technical advances, the authors developed a new digital ocean bottom seismometer and hydrophone (DOBSH) and new portable digital event recorder (PDER). In this paper, only the details for the DOBSH are described. The PDER consists of the same electronics as the DOBSH, except for some minor differences.

Hardware description

External views of the DOBSH and PDER are seen in Figs. 1 and 2,

Fig. 1. External view of DOBSH (Digital Ocean Bottom Seismometer and Hydrophone). Recorder, batteries and seismometers are mounted in a 40 cm diameter glass sphere. Debugging unit is not shown.

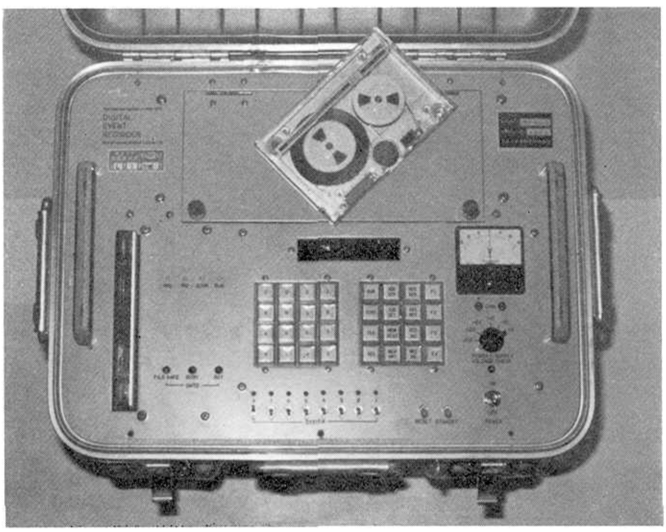


Fig. 2. External view of PDER (Portable Digital Event Recorder). Same electronics as DOBSH are used, but PDER has a key board and a LED display. It also has an AC power supply.

Table 1. Specifications of DOBSH

1. Sensors		
	SEISMOMETER	HYDROPHONE
NUMBER	vertical 1 horizontal 1	pressure 1
MANUFACTURER	Mark-Product Co., Ltd.	OAS Co., Ltd.
MODEL	L-22E	E-2SD
SENSITIVITY	6.69 V/(cm/sec)	450 μV/Pa
RESPONSE	fo=2 Hz	DC~5 kHz
IMPEDANCE/CAPACITANCE	8.54 kΩ	12 nF

2. Amplifier
   1-4 channels; 40-80 dB; input-noise: <0.5 μVpp; frequency response: 0.5~30 Hz flat.
3. Data precision
   12-bit full scale (±2.5 V) (compressed to 4-bit by ADPCM IC and expanded to 12-bit by host-computer or 10-bit by ADPCM IC at sampling rate of 100 Hz or 200 Hz.
4. Recorder
   DFM digital cartridge tape (6400 BPI); 2048 bytes/block (768 bytes/block) at transfer to host-computer; 24 blocks (at 2048 bytes) in max./record.
5. Recording amount (using 555-feet tape)
   18 Mbytes of compressed data; 72 Mbytes of original data; approximately 750 events at 4-channels, 100 Hz sampling rate and 100 seconds of total length of each record.

Table 2. Power requirements

	TAPE DRIVE			CPU-1	CPU-2	ANALOG		
	+24 V	−24 V	+5 V	+5 V	+5 V	+9 V	−9 V	±3.2 V
NORMAL	0.1 A	1.05 A	1.3 A					
REVERSE	1 A	0.19 A	1.3 A	18 mA	12 mA	28.1 mA	14.9 mA	4.0 mA
NOT-WRITING	0	0	0		6 mA			
BATTERIES	Alkaline AA ×44		Alkaline D ×18			Alkaline D ×24		Lithium ×2

respectively. Overall specifications are listed in Table 1 and power requirements in Table 2.

Figure 3 shows the functional diagram of the DOBSH. The functions of each part are summarized in Table 3. Most electronic components of the system consist of CMOS ICs, which are light in weight, small in size and can be operated by batteries. Earthquakes or shots are collected by event triggering algorithm using a micro-processor. The whole unit, including gimbals mounted, seismometers and batteries, is housed in a glass sphere with 40 cm diameter.

The main feature of the event recorder (DOBSH and PDER) is the use of data compression technics. Four ADPCM-ICs (Oki-MSM-5218 RS) are used. These ICs can compress the data length at one sampling from 12 bit to 4 bit. The ADPCM method is one of several in data

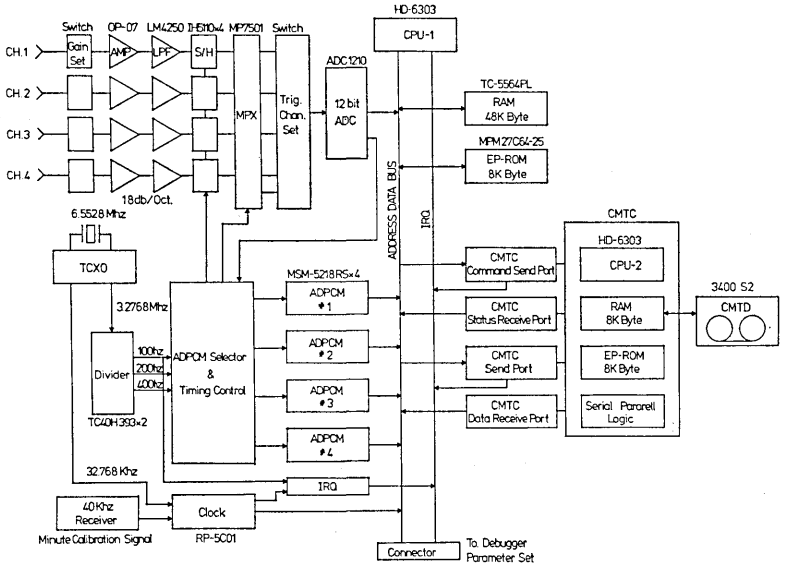


Fig. 3. Block diagram of DOBSH.

Table 3. Functions of each part

1. CPU-1 (HD-6303, 1 MHz CLOCK)
   a. parameter setting and display on LCD (not for DOBSH),
   b. input the ADPCM data (4-bit$\times$1$\sim$4 channels),
   c. input trigger-channel data (12-bit$\times$1 channel),
   d. identification of event,
   e. input time informations (Year, Month, Day, Hour, Minute, Second),
   f. transfer of compressed event data to CPU-2.
2. CPU-2 (HD-6303, 1 MHz CLOCK)
   a. control of cartridge tape drive (Rewind, Forward, Backward, File skip),
   b. formatting of data,
   c. receiving of data from CPU-1,
   d. writing of data on cartridge tape,
   e. power on/off of tape drive and formatter-board,
   f. transmitting of data to host-computer by RS-232C (19.2 KBaud).
3. ADPCM (MSM-5218RS$\times$4)
   a. data compression from 12 bit to 4 bit,
   b. output of 10 bit synthesized data by using ADPCM-IC on real time monitor and play-back mode.
4. CLOCK (RP-5C01)
   a. transfer of time information to CPU-1,
   b. automatic adjustment of clock by input of a minute pulse, supplied by master clock or 40 kHz receiver (within several micro-seconds),
   c. 2×10^{-7} in precision over $0°\sim40°$C,
   d. supply of 100 Hz or 200 Hz key pulse for beginning-time of A/D conversion,
   e. supply of 1 Hz and 1/4 Hz key pulses for triggering summation interruption.

compression technics (also known as speech synthesis). In the design phases for the DOBSH, we tested the effectiveness of ADPM, using the same IC as adopted and by software, and confirmed its effectiveness (KANJO *et al.*, 1983). The details of this method are described in text books on speech synthesis (e.g., AGUI and NAKAJIMA, 1980). A brief review of the ADPCM method is given in Appendix 1. Although the above IC was originally operated in the frequency range from 4 to 8 kHz because of the range of speech frequency bands, we use this IC at a 100 Hz or 200 Hz sampling rate. By 12 bit to 4 bit data compression, the total amount of data that can be recorded on a tape is increased fourfold. The usual 12 bit data are handled as two bytes, but the 12 bit data in the present system are stored in a half byte.

The output from these seismometers and the hydrophone goes to four ADPCM-ICs through amplifiers, anti-aliasing filters, sample and holds (S/H), a multiplexer, a 12 bit Analog to Digital (A/D) converter and a demultiplexer. The 4 bit data supplied by the ADPCM devices is stored as a half byte in RAM. The maximum size for data storage is 48 kB, which corresponds to 16 minutes of record on one channel and 100 Hz sampling rate. The summation of absolute values of original data (12 bit data length) during a quarter second (see Appendix 2) is stored in memory. This a quarter second summation is used for triggering by an event.

Two 8 bit micro-processors (Hitachi HD-6303) are used. The software of the HD-6303 is an upgrade compatible to Motorola 8 bit microprocessor 6802. In addition to the 6802 instruction sets, the CPU (HD-6303) has several additional functions: pipe-line processing, sleep mode (sleeping during non-operation), an instruction for multiplying, etc. The power consumption is very small compared to MOS (Metal Oxide Semiconductor) CPU such as Motorola 6802. The CPU-1 is used for event triggering, parameter setting, control of crystal clock and transfer of the triggering data to CPU-2. The CPU-2 acts to receive the compressed data of an event from CPU-1 and to transfer these data to a cartridge (model CMTD-3400S, DEI Co. Ltd.). The CPU-2 is in a sleep mode except during the recording of data on cartrige tape.

The power of the cartridge tape drive is also turned on only during the recording of data. The saving of data with 4-channel signals and two minutes long in magnetic tape can be completed within four seconds. The total time for writing on the whole tape is approximately 50 minutes. By turning off the power, the total power consumption is drastically decreased (Table 2). To avoid losing the tape position due to the power-off, the last position is stored in memory. The tape drive, which has four tracks, was modified to serpentine-like taperunning (tracks 2 and 4 run in reverse direction) to avoid losing some data during the rewinding of the whole tape.

The programs for operating the DOBSH are stored in CMOS 64 kbit P-ROM (Programmable Read Only Memory) (Fujitsu-MPM-27C64-25). The use of CMOS 64 kbit RAM (Toshiba-TC-5564PL) also decreased power consumption and improved space capacity.

Time information such as year, month, day, hour and second, is processed by a clock-CPU (Ricoh-RP-5C01). An output of 6.5528 MHz TCXO (Temperature compensated Crystal Oscillator) is fed into this clock-processor. The TCXO has a precision of 2×10^{-7} over 0° to 40°C. The time information is kept in the memory of the clock-processor. The clock can be adjusted within several microseconds by a one minute pulse supplied by a master precision clock or a 40 kHz standard time radio broadcasting which is recently available in Japan with the merit of clear ground-wave arrivals, avoiding the frequent appearance of sky-waves in short wave bands such as 5, 10 and 15MHz (known as WWV or JJY). The CPU-1 receives time data from the memory of the clock-processor at the completion of triggering. The 100 Hz or 200 Hz, is used for key pulses in A/D conversion and 1/4 Hz and 1 Hz are used for triggering summation.

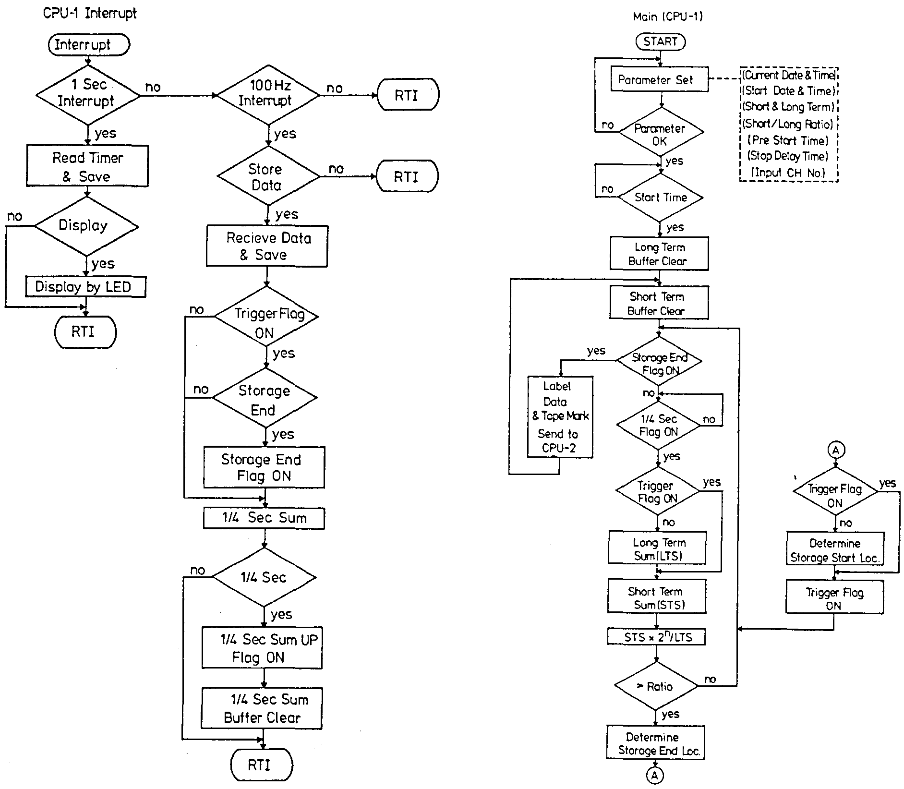
The data recorded in tape can be play-backed through the ADPCM-ICs which have 10 bit D/A converters. The data are also able to be recovered by software.

Software description

The major functions of the software are: parameter setting, event identification, data transfer to the CPU-2 and recording of data on the cartridge tape.

Figure 4 shows the flow chart of CPU-1. At the beginning, an up-date and parameters such as short-term-duration, long-term duration, threshold level, pre-event buffering (PEB) time, post-event-delay (PED) time and preset start time are entered. The identification of an event is performed by a well-known algorithm: ratio of short-term sum to long-term sum. An event is identified when the ratio is greater than the threshold level given by an operator at the parameter setting (see Appendix 2). By the use of a quarter second summation the memory is greatly saved. Since analog to digital conversion is performed by the interruption mode on the CPU with each 10 mili-seconds (100 Hz) or 5 mili-seconds (200 Hz) pulse, input data are not lost during the event identification process.

After the event identification, the CPU-1 continues data buffering



(A) (B)

Fig. 4. Flow chart of CPU-1. (A), interrupt sequence; (B), main flow chart.

for the event until the end of post-event-delay (PED) time. At the end of the PED time, if the ratio is still greater than the threshold level, the data buffering is continued until the next delay time. This process is ended by full of data memory or a decrease of the ratio itself. The event data during the pre-event buffering (PEB) and post-event delay (PED) are transferred to the CPU-2 with the time information obtained from the clock-processor.

The flow chart of CPU-2 is shown in Fig. 5. The CPU-2 is awakened from the sleep mode by an interruption signal supplied by CPU-1. Power for the cartridge tape drive and the format-control-board are turned on. The event data which are received from CPU-1 are arranged in special format and are transferred to the cartridge tape. 2,048 bytes are transferred as one-block in blocking size to the tape. A header block contains information such as setting parameters, the total number of blocks for one event and the time the event triggered. During the CPU-2 operations, the CPU-1 continues A/D conversion. After comple-

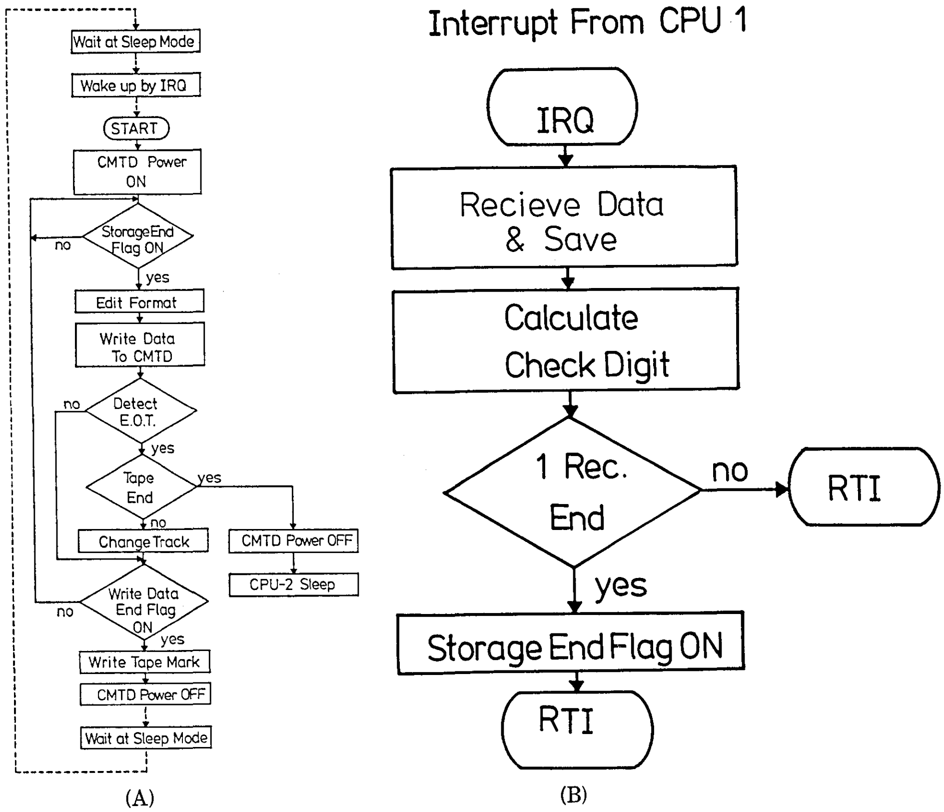


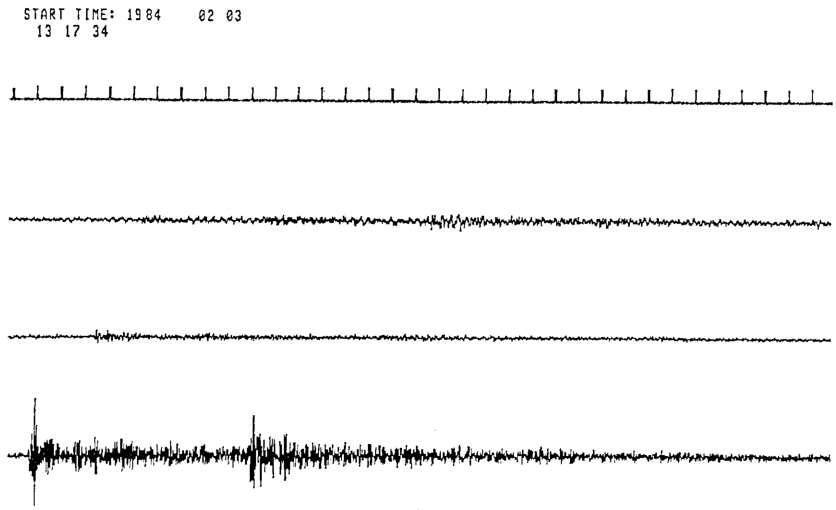
Fig. 5. Flow chart of CPU-2. CPU-2 receives data from CPU-1 and transmits to CMTD (Cartridge Magnetic Tape Drive).

tion of the data recording, power for the tape drive and the format-control-board is turned off and CPU-2 enters into the sleep mode.

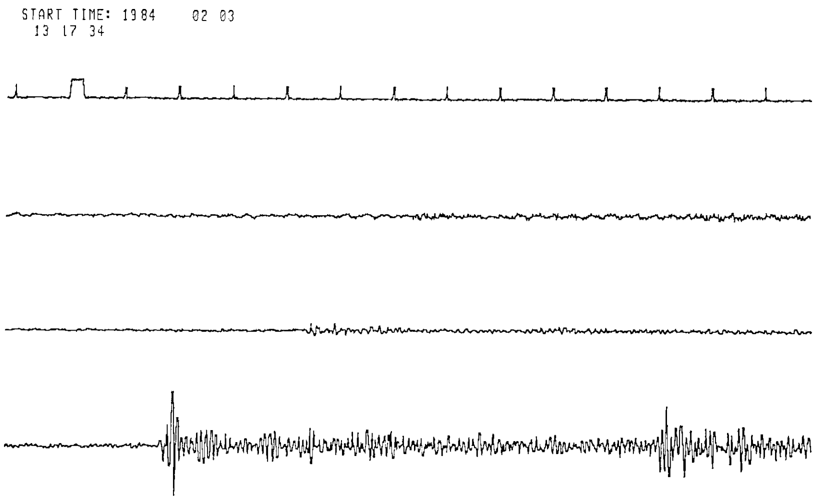
The CPU-2 can also work on primitive drive controls such as rewind, file skip, etc. By the addition of a debugging unit which has a communication board, the data saved in the cartridge can be sent to a host computer through an RS-232C communication linkage. The baud-rate is up to 19.2 kBaud (kBit/second). The entire data are saved on a disk of the host computer (Harris H-80 mini-computer). The compressed data for the events are synthesized by the host computer and displayed on a graphic-display (similar to the graphic display model DS-301A manufactured by Daikin Co., Ltd.).

Field experiments

An example of a natural earthquake recorded by the DOBSH is shown in Fig. 6. In this case, telemetered data collecting in the



(A)



(B)

Fig. 6. An example of triggered events (6A). Top: referenced clock with ticks showing sec. mark. From the second to bottom: records for three different stations gathered by telemeter link. No filter and no smoothing used. 4 seconds and 64 seconds are used for times of short-term sum and long-term sum, respectively. Threshold level was chosen as 4. Other parameters are listed in Table 4. Expansion of Fig. 6A in horizontal scale is shown in Fig. 6B.

Earthquake Research Institute was used for simulation. Data recovery from the compressed-form was made by software.

Two actual ocean deployments of DOBSH were carried out in the Mariana Trough and the Okinawa Trough during 1984. In the first

Table 4. Parameters used at Mariana Trough

Pre-event buffering (PEB) time	50 sec			
Post-event delay (PED) time	50 sec			
STS (short time sum)	4 sec			
LTS (long time sum)	64 sec			
TLSH (threshold level)	4			
Sampling rate	100 Hz			
Channels	V (2 Hz),	H (2 Hz),	H (4.5 Hz),	HYD
Amplifier Gains	40 dB	40 dB	40 dB	40 dB

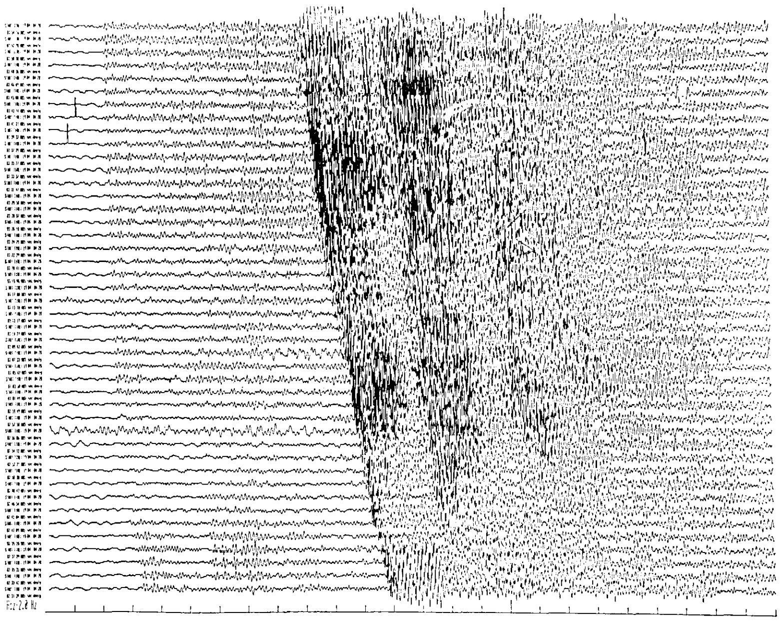


Fig. 7. Example of air-gun records which were obtained in Mariana Trough. Parameters used are listed in Table 4. Air-gun was shot approximately every two minutes. No mis-triggering and no shots lost during experiments except during irregular shot intervals.

test deployment in the Mariana Trough (see Table 4 for parameters used), 400 events which are saved in two third of the whole tape were triggered. Most of events were air-gun shots. Unfortunately, the rest of the records could not be read because of a voltage drop for ± 24 V power system due to continuous triggering by air-gun shots. However, triggering itself was found to have had worked correctly. Part of the results is shown in Fig. 7. After adding the necessary number of batteries to ± 24 V power system, the DOBSH was deployed in the Okinawa Trough. Although DOBSH was retrieved after the explosion experiment, all the explosions, most of the air-gun shots and several tens of natural earthquakes were correctly triggered. Some of air-gun shots were lost due to anomalously irregular shot intervals.

Conclusions

A new digital ocean bottom seimometer and hydrophone (DOBSH) has been developed and the same electronics have been applied to a new portable digital event recorder (PDER). Both instruments are designed to have a large data storage and low power consumption. To achieve the large amount of data storage, an ADPCM method was introduced. At recording, the 12 bit data are compressed to 4 bit by ADPCM-ICs. A triggered event is saved in compressed-form on a cartrige tape. The event is recovered in original form by software on a mini-computer or by a similar ADPCM-IC. By use of ADPCM technics, the total amount of data stored on a cartridge tape is expanded to 72 MB when the data are recovered in original form. Approximately 750 events can be recorded on 4-channels with 100 Hz sampling and each 2 minutes in duration by each deployment of DOBSH. Two CMOS 8 bit microprocessors are used. One is for data collection and event identification, and the other is for control of a cartridge tape drive. Battery operation was achieved by sleeping of the second CPU and a power-off mode for the cartridge tape drive and its related circuit during non-recording time.

Data collected by DOBSH can be easily used. For example, data obtained at the Mariana Trough and the Okinawa Trough were quickly processed. In contrast to this, data obtained by analog system during the same experiments as above have to be worked for event picking, monitor play-back, A/D conversion and display.

Although the present system uses a 12 bit A/D converter, 14 bit or 16 bit A/D conversion is possible for a second generation of the present DOBSH. However, use of a 14 bit or 16 bit A/D converter is especially difficult because of large power requirements for such devices. Another approach to achieving large dynamic range may be automatic-ranging. The authors are investigating the use of this method. The DOBSH can be used for the comparison between real records and synthetic records. By collection of large number of natural earthquakes, spectral changes of foreshocks and aftershocks of a big event may be confirmed. Aftershock observations are one of the most needed applications of the DOBSH.

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Appendix 1. ADPCM method

If a datum at the time t is X_t, the datum at subsequent time $(t+1)$ is

$$X_{t+1}=X_t+\Delta X_t. \tag{A1-1}$$

ΔX_t is the difference of data values between the time t and the time $(t+1)$. In DPCM, ΔX_t is quantitized. For example, if we use four bit quantization for the diffence ΔX_t, $\overline{\Delta X_t}$ (quantized difference) is expressed by

$$\overline{\Delta X_t}=A*\Delta_1+B*\Delta_2+C*\Delta_3+D*\Delta_4. \qquad \text{(A1-2)}$$

$A \sim D$ are 0 or 1 and $\Delta_1 \sim \Delta_4$ are quantization steps. In DPCM, $\Delta_1 \sim \Delta_4$ are constant through analysis of data. On the other hand, ADPCM changes $\Delta_1 \sim \Delta_4$ values.

$$\Delta_l=2^m * W^k * (1/2)^{l-1} \quad (l=1\sim 4), \qquad \text{(A1-3)}$$

m and W are constants chosen as appropriate numbers. When amplitude varies greatly, k is selected as large. When amplitude varies little, k is selected as small.

Appendix 2. Triggering algorithm

A ratio of short term and long term, which is a well known algorithm, is compared to the threshold for triggering. By limitation of memory, a quarter second summation is used instead of data at each sampling. Trigger identification is done every quarter second.

A sum of the quarter second is

$$SUM\,4(k_0)=\sum_{i=j-24}^{j}|Ai| \quad \text{at} \quad t_a. \qquad \text{(A2-1)}$$

$SUM\,4$ is renewed every quarter second. A shorter term sum (STS) is 2^m time of $SUM\,4$,

$$STS(l_0)=\sum_{k=k_0-2^m+1}^{k_0} SUM\,4(k) \quad \text{at} \quad t_a. \qquad \text{(A2-2)}$$

A new STS at following quarter second is given by

$$STS(l_0+1)=STS(l_0)+SUM\,4(k+1)-SUM\,4(k_0-2^m+1)$$
$$\text{at} \quad t_a+\frac{1}{4} \quad \text{sec.} \qquad \text{(A2-3)}$$

A long term sum (LTS) is given by 2^{n+m} of quarter second sum $SUM\,4$:

$$LTS(l_0)=\sum_{k=k_0-2^{m+n}+1}^{k_0} SUM\,4(k) \quad \text{at} \quad t_a. \qquad \text{(A2-4)}$$

A new LTS is given by (A2-4) as similar as (A2-3). In every quarter second, the ratio RA is calculated by

$$RA=STS(l_0)*2^n/LTS(l_0). \qquad \text{(A2-5)}$$

$STS(l_0)*2^n$ is obtained by n-bit left shift of $STS(l_0)$. Only division is calculated in (A2-5). Instead of average, use of summation can avoid the error accumulation.

Finally, the ratio RA is compared to the threshold level $TLSH$. If RA is greater than $TLSH$, input data are concluded as an event.

In our experience, $m=4$, $n=4$, $TLSH \geqq 3$ is effective for mico-earthquakes near Tokyo, Japan. $m=4$ and $n=4$ corresponds to 4 seconds for STS and 64 seconds for LTS, respectively.

ADPCM 方式を用いたマイクロ・プロセッサー制御，大容量ハイドロフォン付きデジタル海底地震計

東京大学地震研究所 笠原順三 高橋正義

海外物産株式会社 松原忠泰 小宮光昇

DOBSH (ハイドロフォン付きデジタル海底地震計) と PDER (ポータブル式イベント・レコーダー) を新たに開発した.

主な特徴を列記すると,

(1) 多数の (4 成分, 100 Hz で各 2 成分記録のとき 750 個分) の地震を記録できる, (2) ADPCM 方式音声合成法を用いている, (3) 長時間バッファー (最大 4 成分×4 分), (4) 2 個の CMOS マイクロ・プロセッサーの使用, である.

イベント・トリガーにより地震を収録する. この際, ADPCM-IC を用いて 12 ビットから 4 ビットへデータ長を圧縮し, デジタル・テープにそのまま記録する. このデータの復元には同じ IC を用いるかあるいはミニコンを用いてソフトウエアーにより行なう. ADPCM 方式の採用により全収録量は実効上 4 倍に増加した. 長さ 555 フィートのテープを用いたとき, 72 MB に相当する原記録を保持できる.

時間に関する情報は時計プロセッサーにより得られる. 時刻は 1 分のパルスか 40 kHz の標準電波信号により正確に同期する.

この DOBSH を用いて, 2 回の実際の海底設置により, これが有効なことが分かった.