Signal Processing in Ocean Bottom Seismographs for Refraction Seismology

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***Abstract*—This paper presents some experimental results on the application of signal processing techniques to underwater seismic signals. The novelty of this paper stems from the fact that it is the first paper, to the best of the authors' knowledge, dealing with a comprehensive processing of signals obtained from active refraction seismology. In particular, this paper has adapted known signal processing techniques to problems such as time of arrival detection (TOA), compression, and representation through conventional images (hodocrones) used in underwater seismology. This work is part of a wider project aimed at the design of a small ocean bottom seismometer (OBS) undertaken by several research and development groups in Spain. This sophisticated easy to handle equipment allows recording useful active and passive seismicity information.**

***Index Terms*—Ocean bottom seismographs, refraction seismology, signal compression, signal processing, wavelets.**

I. Introduction

REFRACTION seismology, as it applies to oceanic exploration, is a novel technique in comparison with traditional reflection techniques. So, it is not strange that related technology has only been developed to a limited extent. On one side, the hardware equipment necessary for signal acquisition called ocean bottom seismometer (OBS) shown in Fig. 1 is manufactured in a "home-made" manner, making the test and validation difficult: Oceanic exploration takes a long period of time, and sometimes the OBS gets lost, making data validation impossible, and thus testing the performance of the OBS itself. There are several countries working on refraction seismology during the last decade, but each of them uses their own equipment, which makes fair comparisons difficult. We can mention the efforts of the Research Center for Marine Geosciences of Kiel University [1], GEOAZUR in France in cooperation with Texas University at Austin [2], Woods–Hole Oceanographic Institution in Massachusetts, SCRIPPS in San Diego [3], and Bullard Laboratory at Cambridge University [4].

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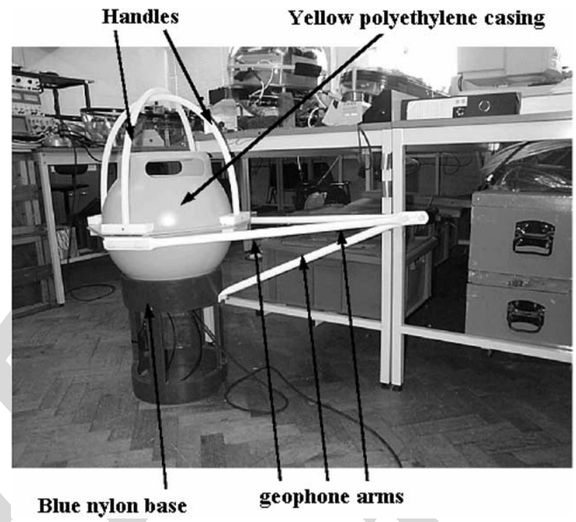

Fig. 1. OBS.

On the other side, and regarding the processing of signals, there are no references, to the best of our knowledge, dealing with the particular application to refraction seismology. The processing of seismic signals has been undoubtedly the motivation and driving factor of many innovations in the signal processing area, remarkably in blind deconvolution, time–frequency distributions, and even neural networks [5]–[8]. However, as we have mentioned, the particularities of refraction seismology, and more specifically underwater, have not been tackled. We can even say that the signal information obtained by the OBS is not easily extracted, and how such signals must be processed to extract all of the available underlying information is still a big issue. As we will see, a "hodocrone" is the usual way to represent in a compact visual way the information contained in a certain amount of signal acquired by the OBS. However, and similar to other kinds of vibrating or seismic signals, it can be expected that more information could be obtained, making a more elaborate processing and representation.

In an attempt to fill this gap, a combined effort of several research centers has been undertaken in our country, Spain, trying to cover every aspect in this interesting technology. For instance, a novel design of OBSs has been carried out, with the first prototypes now under test [4]. These tests have revealed some problems, such as low sensor sensitivity, operational difficulties in instrument recovery, and acquisition system electronic noise level, which are being solved. The largest Spanish oceanic research vessel, the BioHespérides, has been used as the platform for the scientific cruise.

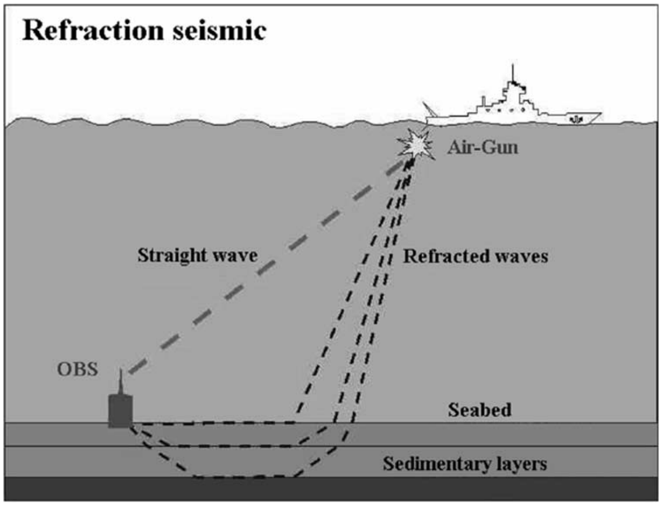

Fig. 2. Seismic refraction.

In parallel, analysis of refraction data, acquired with different OBSs [4] until our own technology is operative, is being analyzed in order to test and validate the most adequate signal processing techniques.

The aim of this paper is to show the results regarding signal acquisition and subsequent processing. The techniques presented here are inspired on well-proved techniques used in other kinds of seismic explorations. Though we are taking the first steps, the results obtained look promising.

II. Experiments

The experiments, developed during marine campaigns, have been designed to collect data related to earth crust at sea from the refracted waves produced in an active seismology process. This process is depicted in Fig. 2. The OBS is deployed at the ocean bottom where it receives the subsequent refracted waves that have been produced by an air gun swept by the vessel at a certain depth underwater. The acoustic wave generated by the air gun propagates through the water and reaches the sea bottom. To achieve a measurable refraction wave, the vessel must be some kilometers away from the OBS position. Since sound speed is higher in the strata than in the water, refracted waves arrive earlier at the OBS than direct waves that travel only through the water to the OBS. The direct acoustic wave through the water is also received by the OBS but does not contain relevant information. As the vessel approaches the OBS vertical point, it is easy to see that refracted, reflected, and direct waves tend to overlap.

It is important to mention that the main data collected are related to time delays between consecutive wave arrivals (refractions), which are in turn related to the type of material, and the instant at which the excitation (bubble) is produced. Therefore, OBS and vessel clocks must be initially synchronized on-board and the time drift due to temperature variation of the equipment environment must be kept within tolerable limits in order to obtain useful data since no communication with the ship can be made for clock synchronization during the experiment, except at instrument recovery process. Refraction seismology has been employed in surface experimentation, where the equipment employed are much simpler and exploration itself is easier. It is easy to check if a given seismometer is properly working or simply needs the batteries to be replaced. However, underwater, these simple operations become impossible, knowing the fact that the operation depth of an OBS is up to 6000 m.

To have an idea of the features of the OBSs employed, from the instrumentation point of view, a short description follows. The equipment is composed of a polyethylene structure that protects a glass sphere (432-mm diameter and 17.7-kg weight). This glass sphere contains the acquisition electronics, the data storage, the acoustic release, and the batteries for power supply. The set is attached to a heavy anchor that allows the deployment of the instrument, and is released acoustically when needed. The sensors that detect vibrations through the water and from the sea bottom waveforms are a hydrophone and a geophone, respectively.

The geophone, model SM6, measures three perpendicular components. The sensor protection is an aluminum housing hanging from the arm of the structure. The geophone is released from the structure 3 h after the deployment, and when it is released, it couples to the sea bottom. The cutoff frequency for each component is 4.5 Hz, the sensibility is 28 V/m/s in every axis, and the distortion is less than 0.3%. The hydrophone is cylindrical and covered with resin. It is attached to a nylon base with a sponge to isolate water vibration from possible structure movements.

The electronic components are encased within the glass sphere. First of all, the acquisition channel includes four 24-bit channels, which contain CS5372/76 (Cirrus Logic) analog to digital converters together with input signal amplification. The CS5372 are two-channel high-dynamic-range fourth-order Δ–Σ modulators specifically designed for geophysical and sonar applications. Used in combination with a CS5376 digital filter, a unique high-resolution A/D measurement system results that all together provide a higher dynamic range of 124 dB at 411-Hz bandwidth and lower total harmonic distortion than other industry modulators while consuming significantly less power per channel. The modulators generate an oversampled serial bit stream at 512 kb/s when operated with a clock frequency of 2.048 MHz. A CPU card, with a 32-bit M68332 Motorola processor, takes care of the data processing and data exchange of the data arriving from the ADC card through a QSPI serial port. It can be run between 8 and 16 MHz, the data rate depending on the process.

Massive data storage is currently accomplished through hard disk drives. The use of hard disks in OBSs is the cause of several problems that affect both the autonomy of the instrument and more importantly data quality. In this case, the hard disk is composed of an electric motor for rotation that results in a great deal of power consumption at power up and the electronic noise generated during this process is reflected on the data collected continuously. A new low power datalogger based on Compactflash memory cards has already been designed and is currently under test. The problems mentioned are expected to be solved, giving rise to a high-resolution acquisition system suitable for long-term seismic data acquisition, reducing the power consumption, and improving the data quality.

All the necessary signals for the datalogger to function correctly have to be generated from a single crystal, and being aware of the fact that in any marine seismic application timing is of great importance, a Vectron OC260 32.768-MHz crystal is used offering a stability of $\pm$40 ppb with temperature and an electronic module is designed and built integrating a ICS52701 phased-locked loop generating different signal frequencies for the system, which is synchronized externally with a GPS, allowing a 10-ms precision.

The acoustic release activates the two circuits of the mechanical release, applying current through a wire that is burnt by an electrolytic process. It is located in the front part of the upper hemisphere. The integrated EPROM stores the preprogrammed signal frequencies and codes necessary for the correct release operation and communication with the on-board Telecommand Unit that sends the release order.

III. Problem

One of the main challenges an OBS must face is the optimization of the amount of information stored. OBSs are autonomous systems, submerged for long periods of time, and the information they acquire is retrieved only when they return to the sea surface. They can be used not only for the mentioned active seismology but also for passive seismology where most of the time there is no useful data to collect. Even in active seismology, most segments of signals are basically noise.

This means that a continuous acquisition, and storage, is by no means efficient. Thus, it is important to detect the relevant instants when the acquisition must start, and store from that point, keeping of course the information on the absolute time. This corresponds to the instants when the excitation from the air-compressed gun in the vessel arrives at the OBS. The correct detection of the instant of arrival of the first signal and the subsequent reflected and refracted replicas are not only important to optimize memory resources but also very relevant to measure time delays and thus the sound speed in different media: water, sediments, etc.

On the other hand, and in order to reduce the amount of stored information, signals must be compressed as much as possible without any loss of significant information. This task can be carried out offline in many different and efficient ways. However, since the compression must be done by the OBS, the computational efficiency of the algorithm is an issue. In addition, and since four different signals are typically acquired (three from a geophone and one from a hydrophone), redundant information can be eliminated, and only the independent data stored. Typically, geophysicists make use of only one geophone axis: the vertical component. This is obviously a waste of resources; either the OBS must be provided with only one geophone in the most appropriate orientation, or if three directions are used, their information should be combined to enhance or extract underlying information.

IV. Solutions Adopted

Wavelet techniques have played a dominant role in seismic signal processing, and refraction seismology will not be an exception. The detection of the time of arrival (TOA) that has been implemented is based on wavelet decomposition, similar to that employed in [9], but adapted to the characteristics of signal at hand. The algorithm basically decomposes the signal in a group of bands and makes the decision based on the most significant one. In this case, as Fig. 3 depicts, two representative bands can be identified (D3 and D4) and not only one. For that reason, the algorithm has been adapted to make the decision based on a combination of both. The simplest way to combine the information of both bands is to multiply their coefficients so that the decision is based on this product. In case the signal characteristics change, either because the experiment is different or just because the sampling rate change, the algorithm should be adapted in the same way. The wavelet family employed is the Haar, which is simple and has demonstrated its suitability in our application. TOA is correctly determined in over 95% of the cases. In the remaining ones, the signal is detected but not correctly triggered.

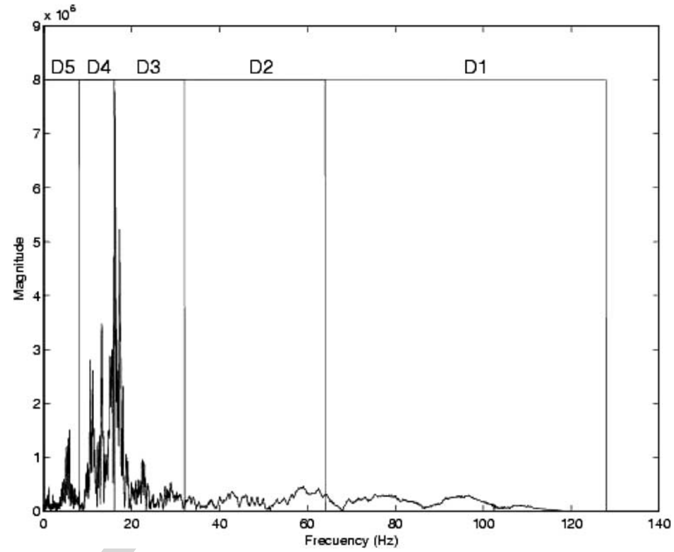

Fig. 3. Spectrum of a typical seismic signal.

Regarding compression techniques, two alternative methods have been implemented and tested. The first one is based on techniques presented in [10]–[12], which are based on a wavelet transform [13] of the signal to be compressed. We have again used the Haar Family but now with only four levels of decomposition in subbands. A further decimation is applied to have a sampling frequency according to the effective bandwidth of each wavelet component. Each sample coefficient was coded with 5 bits.

The implemented algorithm can be split into two independent and consecutive modules: a zero-tree coding and an arithmetic coding. The zero-tree coding is an iterative complex algorithm that transforms the wavelet-decomposed signal into a sequence composed of four different symbols. The most important among them is the symbol called T (zero-tree), which is responsible for the compression. This symbol shows up when the energy level of a coefficient and of those of higher frequency bands related to it is lower than the level of the current coding step. In that case, all these coefficients can be coded by only one symbol (T),

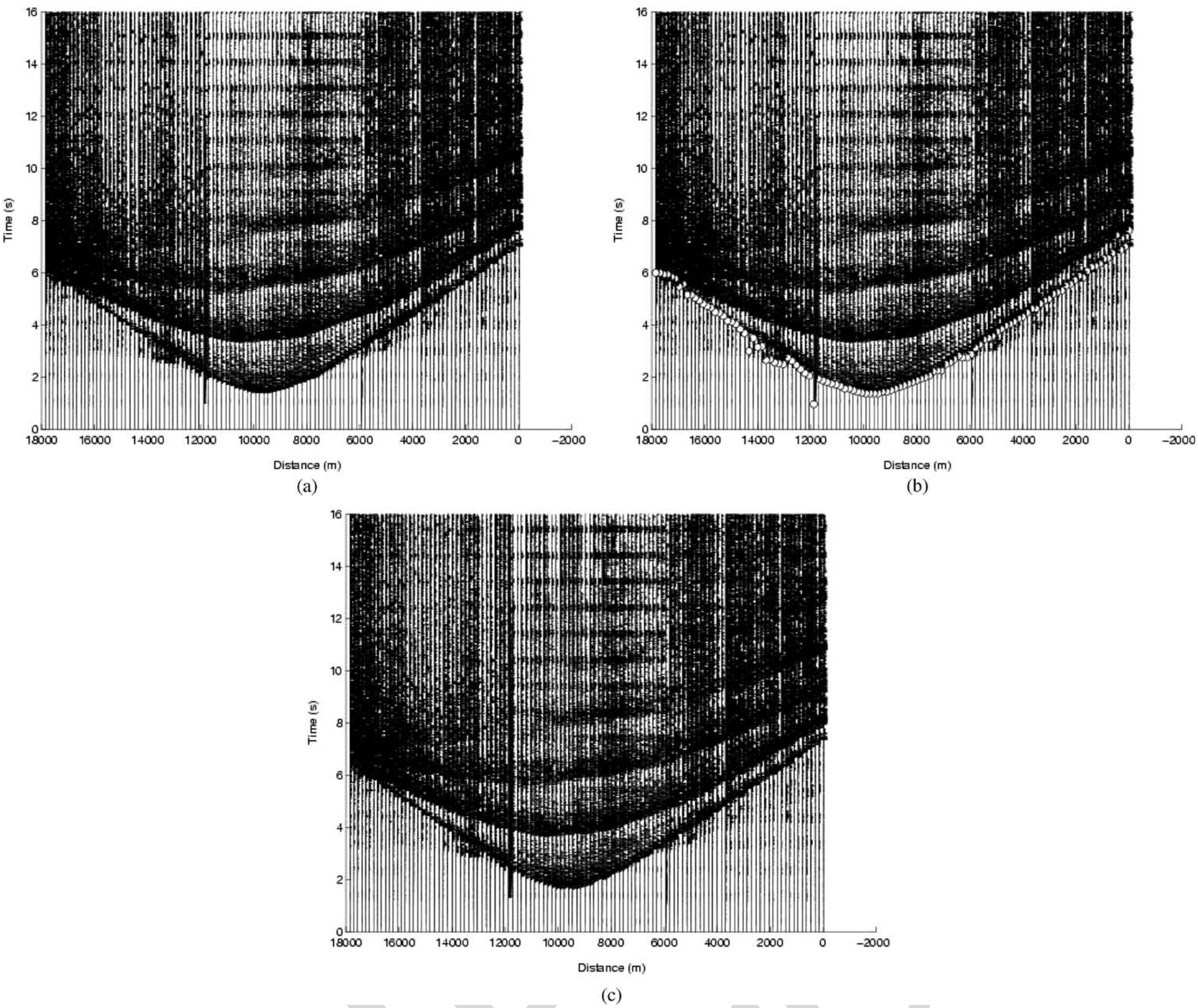

Fig. 4. (a) Original hodocrone. (b) Hodocrone with arrival detection. (c) Hodocrone with compressed data.

resulting in a signal compression. To apply this technique, it is necessary that the original signal be low-pass filtered (Fig. 3) so that the coefficients of higher frequency bands have, in general, lower energy levels than those of lower frequency bands that they are related to. For a more detailed description of this coding technique, readers are addressed to [11] and [12]. The compression indexes obtained in this way are rather high, at the expense of introducing some losses: A typical figure of compression is 78% using 8 K sample blocks, although the number of actual compression depends on the signal.

The second block of the compression algorithm is the arithmetic coding. This technique is based on assigning a variable number of bits to a symbol depending on its occurrence probability. In this way, the coder assigns more bits to less probable symbols and fewer bits to more probable ones. For that reason, this technique only gives good results if the occurrence probability of the symbols is not similar. The zero-tree coder obtains a sequence composed of four different symbols, two of them with higher probability (37% and 35%) than the others (14% each), so that the use of the arithmetic coder is justified. A complete description of this technique is available in [14]. The arithmetic coder increases the compression index; an additional 14% can be obtained, depending again on the signal, increasing the total compression index up to 81%.

The most important limitation of the method described, and in general of wavelet methods, is their computational burden and thus the resulting processing time. To cope with this problem, an alternative method was developed that is more suitable for a real-time implementation within the OBS. The method is based on using first a subband coding [15], instead of a wavelet decomposition, as suggested in [16]. Subband decomposition by filtering is obviously related to wavelet decomposition but has the advantage of a higher computational efficiency.

The idea is now, instead of using zero-trees, to code each subband at a rate proportional to the information contained in the band, and thus not in the same way for all the bands. In this way, samples corresponding to lower frequency bands will be coded using more bits than samples corresponding

TABLE I
CROSS-CORRELATION IN ZERO-TREE ALGORITHM

	4096 Samples	8192 Samples	16384 Samples
Horizontal Geophone 1	99.96%	99.93%	99.90%
Horizontal Geophone 2	99.96%	99.93%	99.98%
Vertical Geophone	99.90%	99.83%	99.73%
Hydrophone	99.86%	99.77%	99.66%

TABLE II
CROSS-CORRELATION SUBBAND CODING

	Scheme 16-08-08	Scheme 20-12-12
Horizontal Geophone 1	97.98%	98.13
Horizontal Geophone 2	97.93%	98.09%
Vertical Geophone	95.54%	95.93%
Hydrophone	95.51%	96.25%

to higher frequency bands that, as Fig. 3 shows, contain less significant information. The compression indexes obtained with subband coder are however lower: up to 58% depending on the signal and the quantification scheme. It goes without saying that subband coding also introduces losses. In the same way as in the method based on wavelet transform, an arithmetic coder is subsequently added as a last step, which can increase the compression index up to 25%, depending again on the signal and the quantification scheme. Typically, the global compression indexes achieved are lower than for the case of wavelet coding. A maximum index of 68% is obtained for subband coding. The advantage is that the computational load can be reduced by factors over 300 for a similar effect in terms of signal integrity.

Regarding the extraction of the independent underlying information from the acquired signals, we applied an independent component analysis (ICA) to the three signals received by the geophone [17]. In case of, for instance, a dominant p-polarization of the seismic wave, only two components should result. This step might also serve to improve the accuracy of the TOA, and of course contribute to an additional compression. Our experience with the application of ICA to the signals at hand shows in fact two dominant, and similar, components with a delay close to 90°. However, we cannot claim they correspond to the two components of an elliptically polarized (Raleigh) wave since we do not yet have alternative procedure to validate such result. As mentioned in Section I, it is not even clear which is the physical information contained in the supposedly independent components.

V. EXPERIMENTAL RESULTS

It is possible to compare original signals and those resulting after the application of different algorithms. However, the correct validation of the results is only given by the final graphical representation the scientists use for their interpretation: the so-called "hodocrone." Such a representation is nothing but a sort of grey-level graphic where the horizontal axis corresponds to distance (vessel displacement) and the vertical axis represents time. The separation between two vertical traces corresponds to the distance between two shots from the vessel.

The image results from the horizontal stacking of successive seismic signals produced at regular time intervals. Fig. 4(a) shows the original signals, as acquired by the OBS, without any processing. In Fig. 4(b), we show the same signals, but marking in white on every signal the time instant that has been detected by the algorithm as the instant of arrival. It goes without saying that the algorithms works properly in almost all cases. By the way, the slope of the asymptote of the white curve should correspond to the sound speed in water (1.5 km/seg approximately).

Fig. 4(c) shows the hodocrone built up of compressed waves obtained by making use of the subband method. No significant differences can be appreciated with respect to the original hodocrone, which means that no loss of significant information has been produced. Apart from the more subjective information resulting from the observation of hodochrone images, it is also possible to give a more objective evaluation of the similarity between compressed and raw waves. In Tables I and II, we show some figures representing the correlation between both signals for the geophones and hydrophone obtained using the Matlab xcorr function. It is obvious, as we initially predicted, that the results are worse for the subband decomposition. However, any of the methods seem to give excellent results.

As a final note, though this is not related to the results of our algorithms, we would like to note that the refracted waves should appear in the region below the white curve. Refracted waves travel faster than direct waves received by the OBS through water, since sound speed in solid media is higher than in water. When the vessel is kilometers away from the OBS, this effect becomes dominant. However, and for the signals at hand, refraction waves are hardly appreciated. This seems to be due probably to the poor quality of the original signals, due to the lack of sensitivity of the geophones used.

VI. Conclusion

In this paper, we have described experiments and instrumentation related to active refraction seismology, which is an exploration technique for undersea investigation. Then, we have focused on the use and application of several signal processing techniques to properly compress and extract the information from the measured signals. While these signal processing techniques are widely used in other kinds of seismic exploration methods, this is, to the best of our knowledge, the first attempt to apply them to refraction seismology.

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He has specialized in the design and implementation of data acquisition systems for marine seismic instrumentation.

AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

AQ1 = Please provide the expanded form of the acronym "EPROM."
AQ2 = Please provide publisher name in Ref. [12].
Notes: 1) Reference [18] was not cited anywhere in the body of the text.
2) Figures 1–4 contain pixelated text with shadows.

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