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.

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

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

179 III. PROBLEM

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

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

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

214 IV. SOLUTIONS ADOPTED

215 Wavelet techniques have played a dominant role in seismic
 216 signal processing, and refraction seismology will not be an

Fig. 3. Spectrum of a typical seismic signal.

exception. The detection of the time of arrival (TOA) that has
 217 been implemented is based on wavelet decomposition, similar
 218 to that employed in [9], but adapted to the characteristics of
 219 signal at hand. The algorithm basically decomposes the signal
 220 in a group of bands and makes the decision based on the most
 221 significant one. In this case, as Fig. 3 depicts, two representative
 222 bands can be identified (D3 and D4) and not only one. For that
 223 reason, the algorithm has been adapted to make the decision
 224 based on a combination of both. The simplest way to combine
 225 the information of both bands is to multiply their coefficients
 226 so that the decision is based on this product. In case the
 227 signal characteristics change, either because the experiment is
 228 different or just because the sampling rate change, the algo-
 229 rithm should be adapted in the same way. The wavelet family
 230 employed is the Haar, which is simple and has demonstrated
 231 its suitability in our application. TOA is correctly determined
 232 in over 95% of the cases. In the remaining ones, the signal is
 233 detected but not correctly triggered.

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

The implemented algorithm can be split into two independent
 244 and consecutive modules: a zero-tree coding and an arithmetic
 245 coding. The zero-tree coding is an iterative complex algorithm
 246 that transforms the wavelet-decomposed signal into a sequence
 247 composed of four different symbols. The most important among
 248 them is the symbol called T (zero-tree), which is responsible for
 249 the compression. This symbol shows up when the energy level
 250 of a coefficient and of those of higher frequency bands related
 251 to it is lower than the level of the current coding step. In that
 252 case, all these coefficients can be coded by only one symbol (T),
 253

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

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

264 The second block of the compression algorithm is the arith-
 265 metic coding. This technique is based on assigning a vari-
 266 able number of bits to a symbol depending on its occurrence
 267 probability. In this way, the coder assigns more bits to less
 268 probable symbols and fewer bits to more probable ones. For that
 269 reason, this technique only gives good results if the occurrence
 270 probability of the symbols is not similar. The zero-tree coder
 271 obtains a sequence composed of four different symbols, two
 272 of them with higher probability (37% and 35%) than the others

(14% each), so that the use of the arithmetic coder is justified. A
 273 complete description of this technique is available in [14]. The
 274 arithmetic coder increases the compression index; an additional
 275 14% can be obtained, depending again on the signal, increasing
 276 the total compression index up to 81%.
 277

The most important limitation of the method described, and
 278 in general of wavelet methods, is their computational burden
 279 and thus the resulting processing time. To cope with this prob-
 280 lem, an alternative method was developed that is more suitable
 281 for a real-time implementation within the OBS. The method is
 282 based on using first a subband coding [15], instead of a wavelet
 283 decomposition, as suggested in [16]. Subband decomposition
 284 by filtering is obviously related to wavelet decomposition but
 285 has the advantage of a higher computational efficiency.
 286

The idea is now, instead of using zero-trees, to code each
 287 subband at a rate proportional to the information contained
 288 in the band, and thus not in the same way for all the bands.
 289 In this way, samples corresponding to lower frequency bands
 290 will be coded using more bits than samples corresponding to
 291

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%

292 to higher frequency bands that, as Fig. 3 shows, contain less
293 significant information. The compression indexes obtained with
294 subband coder are however lower: up to 58% depending on the
295 signal and the quantification scheme. It goes without saying that
296 subband coding also introduces losses. In the same way as in
297 the method based on wavelet transform, an arithmetic coder is
298 subsequently added as a last step, which can increase the com-
299 pression index up to 25%, depending again on the signal and
300 the quantification scheme. Typically, the global compression
301 indexes achieved are lower than for the case of wavelet coding.
302 A maximum index of 68% is obtained for subband coding. The
303 advantage is that the computational load can be reduced by
304 factors over 300 for a similar effect in terms of signal integrity.
305 Regarding the extraction of the independent underlying in-
306 formation from the acquired signals, we applied an indepen-
307 dent component analysis (ICA) to the three signals received
308 by the geophone [17]. In case of, for instance, a dominant
309 p-polarization of the seismic wave, only two components
310 should result. This step might also serve to improve the ac-
311 curacy of the TOA, and of course contribute to an additional
312 compression. Our experience with the application of ICA to
313 the signals at hand shows in fact two dominant, and similar,
314 components with a delay close to 90° . However, we cannot
315 claim they correspond to the two components of an elliptically
316 polarized (Raleigh) wave since we do not yet have alternative
317 procedure to validate such result. As mentioned in Section I, it
318 is not even clear which is the physical information contained in
319 the supposedly independent components.

V. EXPERIMENTAL RESULTS

321 It is possible to compare original signals and those resulting
322 after the application of different algorithms. However, the cor-
323 rect validation of the results is only given by the final graphical

representation the scientists use for their interpretation: the so- 324
called “hodocrone.” Such a representation is nothing but a sort 325
of grey-level graphic where the horizontal axis corresponds to 326
distance (vessel displacement) and the vertical axis represents 327
time. The separation between two vertical traces corresponds to 328
the distance between two shots from the vessel. 329

The image results from the horizontal stacking of successive 330
seismic signals produced at regular time intervals. Fig. 4(a) 331
shows the original signals, as acquired by the OBS, without 332
any processing. In Fig. 4(b), we show the same signals, but 333
marking in white on every signal the time instant that has 334
been detected by the algorithm as the instant of arrival. It goes 335
without saying that the algorithms works properly in almost all 336
cases. By the way, the slope of the asymptote of the white curve 337
should correspond to the sound speed in water (1.5 km/seg 338
approximately). 339

Fig. 4(c) shows the hodocrone built up of compressed waves 340
obtained by making use of the subband method. No significant 341
differences can be appreciated with respect to the original 342
hodocrone, which means that no loss of significant information 343
has been produced. Apart from the more subjective information 344
resulting from the observation of hodochrone images, it is also 345
possible to give a more objective evaluation of the similarity 346
between compressed and raw waves. In Tables I and II, we show 347
some figures representing the correlation between both signals 348
for the geophones and hydrophone obtained using the Matlab 349
xcorr function. It is obvious, as we initially predicted, that the 350
results are worse for the subband decomposition. However, any 351
of the methods seem to give excellent results. 352

As a final note, though this is not related to the results of 353
our algorithms, we would like to note that the refracted waves 354
should appear in the region below the white curve. Refracted 355
waves travel faster than direct waves received by the OBS 356
through water, since sound speed in solid media is higher than 357

358 in water. When the vessel is kilometers away from the OBS,
 359 this effect becomes dominant. However, and for the signals at
 360 hand, refraction waves are hardly appreciated. This seems to be
 361 due probably to the poor quality of the original signals, due to
 362 the lack of sensitivity of the geophones used.

VI. CONCLUSION

364 In this paper, we have described experiments and instru-
 365 mentation related to active refraction seismology, which is an
 366 exploration technique for undersea investigation. Then, we have
 367 focused on the use and application of several signal processing
 368 techniques to properly compress and extract the information
 369 from the measured signals. While these signal processing tech-
 370 niques are widely used in other kinds of seismic exploration
 371 methods, this is, to the best of our knowledge, the first attempt
 372 to apply them to refraction seismology.

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AUTHOR QUERIES

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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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