# Suppression of water-column multiples in multicomponent seafloor data: Preliminary results and proposal

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## ABSTRACT

The dual-sensor method has had a good deal of success in attenuating water-column multiples in multicomponent seafloor surveys. The method in its simplest form has been refined by various workers to take into account some of the factors otherwise neglected. These include: (1) nonvertical incidence implying variation of reflection and transmission coefficients with angle of incidence, (2) nonvertical incidence, again, requiring provision for S waves; (3) inclusion of the significant contributions to these multiples generated at the source end and thus multiple energy arriving also from below; (4) the effect of varying water depth; and (5) significant differences in the two wavelets, both in phase and amplitude spectra. We propose to review improvements that have been made and try to develop further refinements.

There are two essentially different types of water-column reverberations: (1) those that are confined to the water layer and (2) those that follow the arrivals of primary reflections. Some preliminary numerical results are given for the second type. These show that no universal scaling factor exists that can be used to eliminate multiples of all orders by summation of hydrophone and vertical geophone traces. For the first type, however, all such reverberations arrive from above and provision just for variation of reflection and transmission coefficients with angle of incidence, perhaps in the $\tau$-$p$ domain, could lead to great improvement.

## INTRODUCTION

In marine seismic datasets, the multiples that result from reverberation of P waves in the water column can be very strong and often cause serious problems for processors and interpreters (Figure 1). Many authors have presented methods that seek to suppress these multiples, both in conventional streamer surveys and in ocean-bottom cable (OBC) surveys. This study will only deal with multicomponent OBC or seafloor datasets and will consider almost exclusively methods that rely on combinations of acquired components to attenuate water-column multiples.

Some of the early suggestions for combining instrument components to attenuate energy arriving from above through the water column came from Haggerty (1956), White (1965) and Gal’perin (1974). Loewenthal et al. (1985) showed formally how a separation of upgoing and downgoing wavefields could be effected combining hydrophone and vertical-geophone data. The so-called dual-sensor method of Barr and co-workers was presented by Barr and Sanders (1989) and Barr (1989), and further developed by Dragoset and Barr (1994), Paffenholz and Barr (1995), Barr (1997) and Barr et al. (1997).

In the last few years, a number of refinements and variations on these methods have been presented by, among others: Ball and Corrigan (1996), Amundsen et al. (1998),

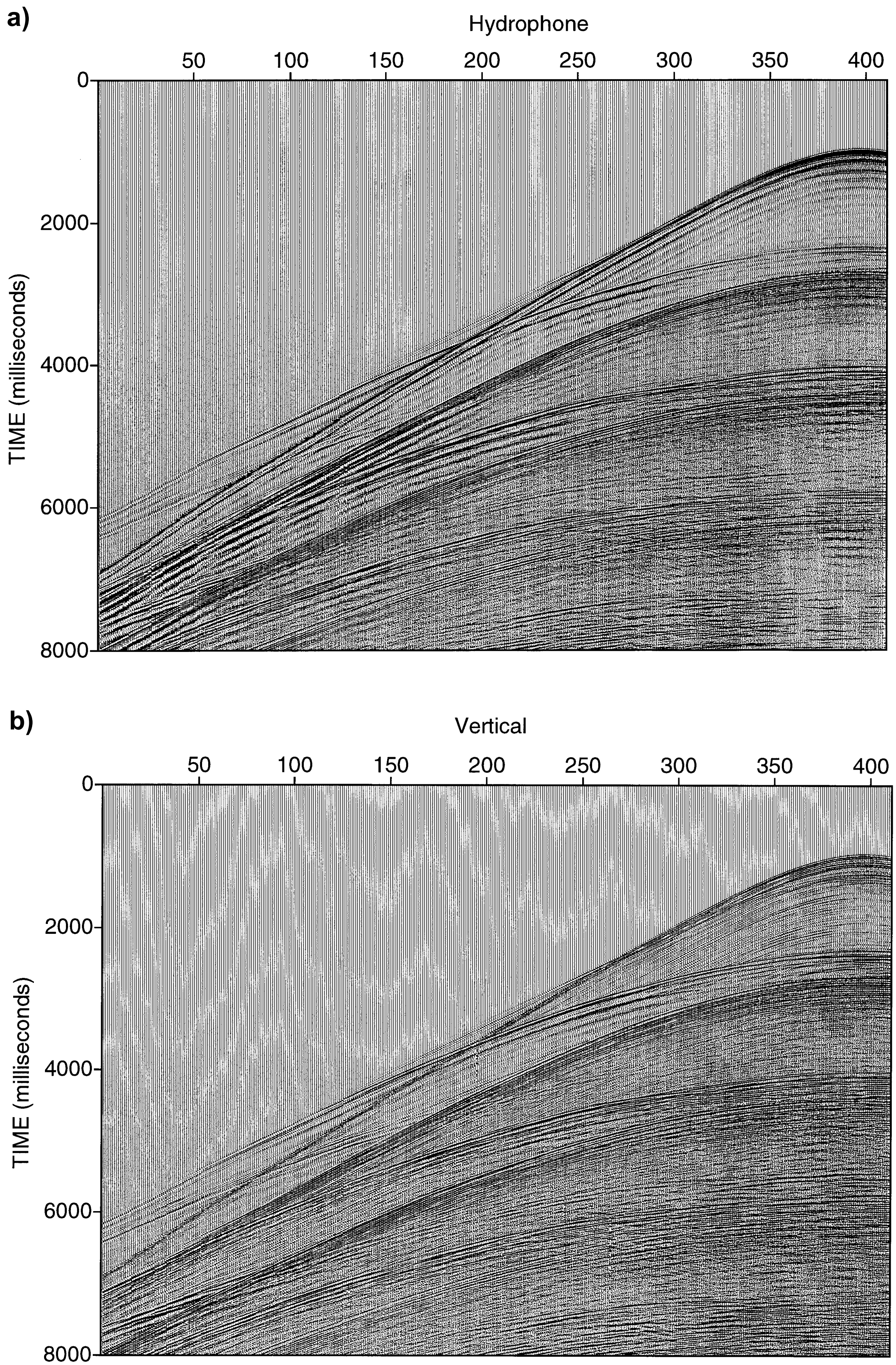



Fig. 1. Common-receiver gathers showing strong water-column multiples up to fourth order (courtesy PGS Reservoir AS).

Bale (1998), Soubaras (1998), Osen et al. (1999), Amundsen (1999) and Liu et al. (1999).

Other methods for suppressing multiples in OBC surveys have been presented based, for example, on the inverse-scattering approach (Matson and Weglein, 1996; Weglein et al., 1997; Ikelle, 1998, 1999a, b; Weglein, 1999), a Fourier-Hankel or *f-k* approach (Dong and Ponton, 1999), incorporation of the known source signature (Johnston and Ziolkowski, 1999), and the so-called adaptive surface-related multiple elimination method (Verschuur et al., 1992; Verschuur and Neumann, 1999).

## THE BASIC DUAL-SENSOR METHOD

The basic tenet of the dual-sensor method is, assuming the SEG recording-polarity standard has been followed (Thigpen et al., 1975; Brown 1999), that upgoing P-wave arrivals will register with the same polarity on a hydrophone and vertical geophone, whereas, downgoing P-wave arrivals will register with the opposite polarity on the two instruments. This presents the theoretical opportunity to scale and sum the two types of gather, as described below, and cancel out the downgoing energy.

Although the basic or simple dual-sensor method has enjoyed definite success in attenuating water-column multiples in multicomponent seafloor data, it could be improved upon. Certainly, a number of improvements or refinements have been presented and adopted by various workers. Nevertheless, in order to consider all possible improvements in this discussion, we would like to start with the method in its most primitive form, wherein hydrophone (W) and vertical-geophone (Z) gathers are simply scaled, either empirically or using knowledge of the seafloor reflection coefficient, then added together.

There are certain assumptions made or factors neglected in this basic application of the method. For example, (1) it assumes vertical incidence, implying that reflection and transmission coefficients are the same for all angles of incidence, when in fact they vary; (2) by assuming vertical incidence, it makes no provision for S waves; (3) by seeking to eliminate only downgoing arrivals, it assumes that all water-column multiples associated with particular primary reflection arrivals are generated at the receiver end of the acquisition path and neglects those of roughly equal energy generated at the source end; (4) it neglects to address the question of whether and how water depth varies; and (5) it assumes that the wavelet is identical on hydrophone (W) and vertical-geophone (Z) gathers. As mentioned, improvements have been proposed for most or all of these areas; however, we wish to revisit them with a view toward assessing these augmentations and finding further improvements in performance.

The theory for this basic or simple dual-sensor method is based on the vertical-incidence acoustic situation of Figure 2. Theoretical amplitudes of arrivals on the hydrophone are computed by summing contributions from all waves propagating in the water, just above the seafloor, at the arrival time. For an arrival incident from below, this is just the transmitted wave; for one incident from above these are the incident and reflected waves. Motion theoretically recorded on a geophone is computed by vector-summing the contributions of all waves propagating in the

**a) For vertical P-wave incidence:**

0: air (vacuum)

$R_{01} = R_0 = 1$

$R_{10} = -R_0 = -1$

1: water (liquid)

$R_{12} = R_1$

$R_{21} = -R_1 = -R_1(\alpha_1, \alpha_2, \rho_1, \rho_2)$

2: sediment (solid)

$$R_{ij} = \frac{Z_j - Z_i}{Z_i + Z_j} \qquad T_{ij} = \frac{2Z_i}{Z_i + Z_j}$$

$$R_{ji} = -R_{ij} \qquad T_{ji} = 2 - T_{ij}$$

Continuity of vertical amplitudes: $1 = R_{ij} + T_{ij}$

Conservation of energy flux: $Z_i \cdot 1 = Z_i R_{ij}^2 + Z_j T_{ij}^2$

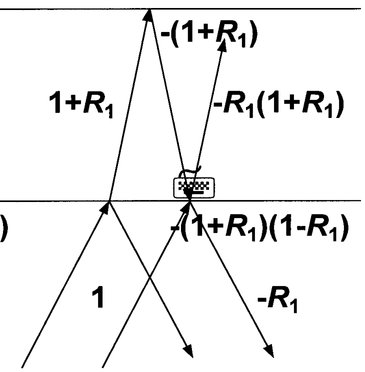
**b) For (near-)vertical acoustic P-wave incidence:**

$R_{01} = R_0 = 1$

$R_{10} = -R_0 = -1$

$R_{12} = R_1$

$R_{21} = -R_1 = -R_1(\alpha_1, \alpha_2, \rho_1, \rho_2)$




| | primary | 1st multiple | 2nd multiple |
|---|---|---|---|
| $W$ phone | $1+R_1$ | $-(1+R_1)(1+R_1)$ | $R_1(1+R_1)^2$ |
| $Z$ phone | $1+R_1$ | $(1-R_1)(1+R_1)$ | $-R_1(1-R_1^2)$ |
| ratio $\frac{W}{Z}$ | $1$ | $-\frac{1+R_1}{1-R_1}$ | $-\frac{1+R_1}{1-R_1}$ |

Fig. 2. The simple physical problem for the basic dual-sensor method; (a) giving definitions of physical quantities and constraints on the reflection and transmission coefficients and acoustic impedances; and (b) showing amplitudes of various reflected and transmitted phases.

seafloor at the arrival time. For incidence from below, these are the incident and reflected waves; for incidence from above this is the transmitted wave. According to the basic dual-sensor theory (e.g. Barr and Sanders, 1989; Barr, 1997), a primary P-wave arrival will register with a hydrophone-to-geophone amplitude ratio given by $W/Z = 1$ (normalizing amplitudes to that of the incident wave). On the other hand, the multiples will register with an amplitude ratio given by $W/Z = -(1 + R_1)/(1 - R_1)$ for any multiple order. Theoretically then, and assuming that W and Z gathers are equalized with respect to primary-reflection amplitudes, scaling geophone traces by the factor $(1 + R_1)/(1 - R_1)$ and adding to them the hydrophone traces will eliminate the multiples and reinforce the primaries.

## REFINING THE DUAL-SENSOR METHOD

### Two different types of water-column reverberation

We consider the first four points above in trying to look at a more complete dual-sensor method. The fifth point, involving the question of the differences in the wavelet on the hydrophone and vertical-component geophone, is a prime focus in another CREWES research project (see Silawongsawat and Margrave, 1999). There are two essentially different types of water-column multiples to consider: (1) those that reverberate purely in the water column, arriving after the direct (one-leg) arrival, travelling along 3, 5, 7,… legs from source to receiver; and (2) those that are associated with primary reflections from subseafloor horizons and that arrive in periodic trains following these primaries. The first type, because they arrive in a single train of a few well separated and periodic bursts, are more easily recognized in raw gathers (Figure 1). In OBC surveys they will necessarily always arrive from above as downgoing energy so we need not consider (3) above for them. The second type involves a periodic train following every single primary arrival – each one of these being, most likely, of lower amplitude than the first type but, being so many such trains, they will constitute a much more convoluted and unrecognizable pattern. This type will have roughly equal contributions from both source and receiver ends and will entail energy arriving both from above and below. For simplicity, we will here treat the two types together, keeping the difference in mind for future reference.

### The potential for improving dual-sensor performance

Of the five areas listed above in which some multiple-attenuation improvements are possible, we focus first on the fact that we no longer can assume vertical incidence. So we have to consider S waves, either as primaries arriving from below, or generated at the seabed by P waves impinging from above or below. Also, reflection and transmission coefficients will now vary with angle of incidence and depend not only on seabottom density and P-wave velocity, but also on S-wave velocity (Figure 3). To determine just how they vary, the Zoeppritz equations for the case of a solid/solid interface, given by Aki and Richards (1980) have been coded up, with augmentation to include the liquid/solid case.

Theoretical amplitudes of primary reflections and several orders of their associated water-column multiples (normalized to the amplitude of the impinging primary) were computed for each of the three instruments: hydrophone (W), vertical geophone (Z)

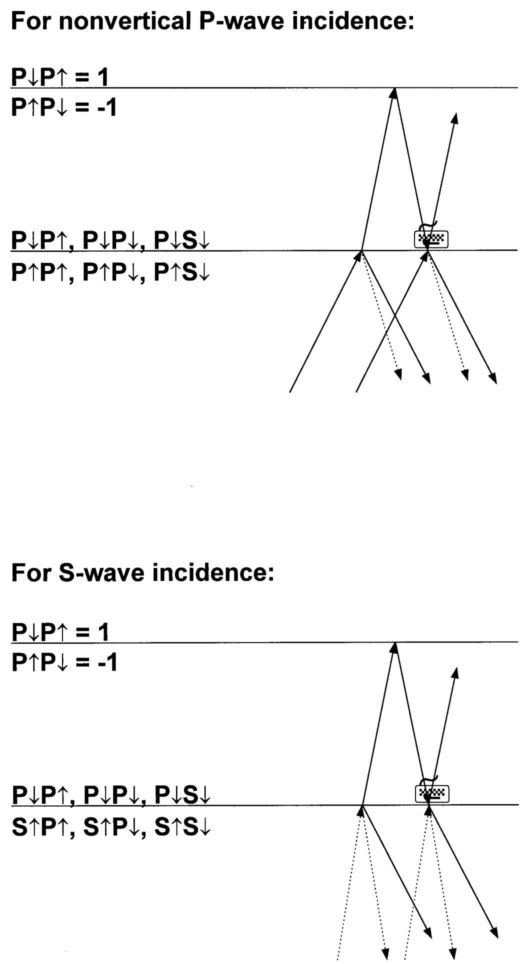



Fig. 3. Primary reflections at nonvertical incidence and their associated receiver-end first-order water-column multiples. All of the reflection and refraction coefficients shown play a role and all vary with angle of incidence

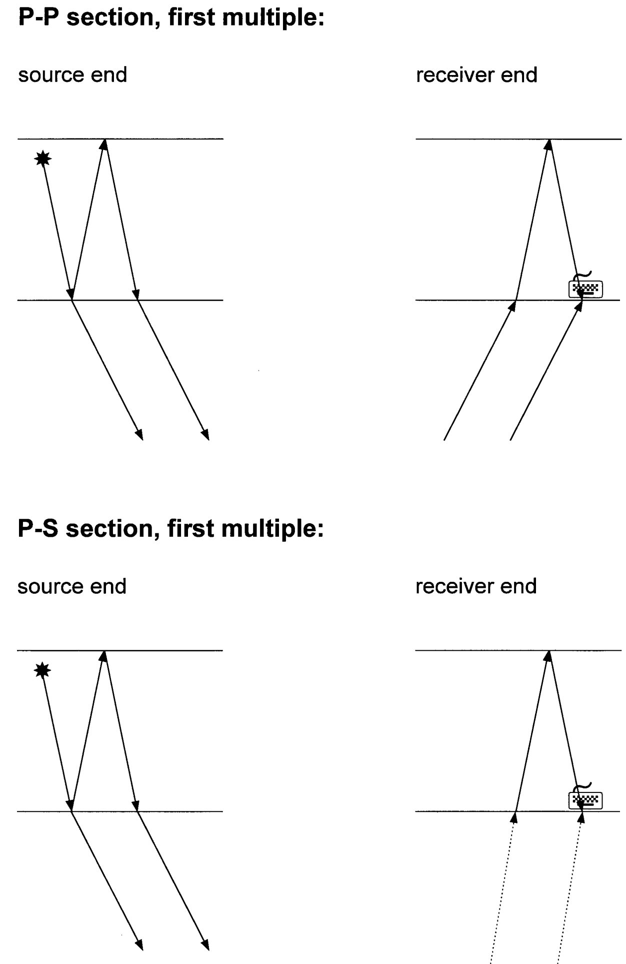



Fig. 4. Sketch showing the contributions from source and receiver ends to the first-order water-column multiples following a primary P-P or P-S reflection arrival; for the case of uniform water depth these two have equal traveltimes and are of similar energy.

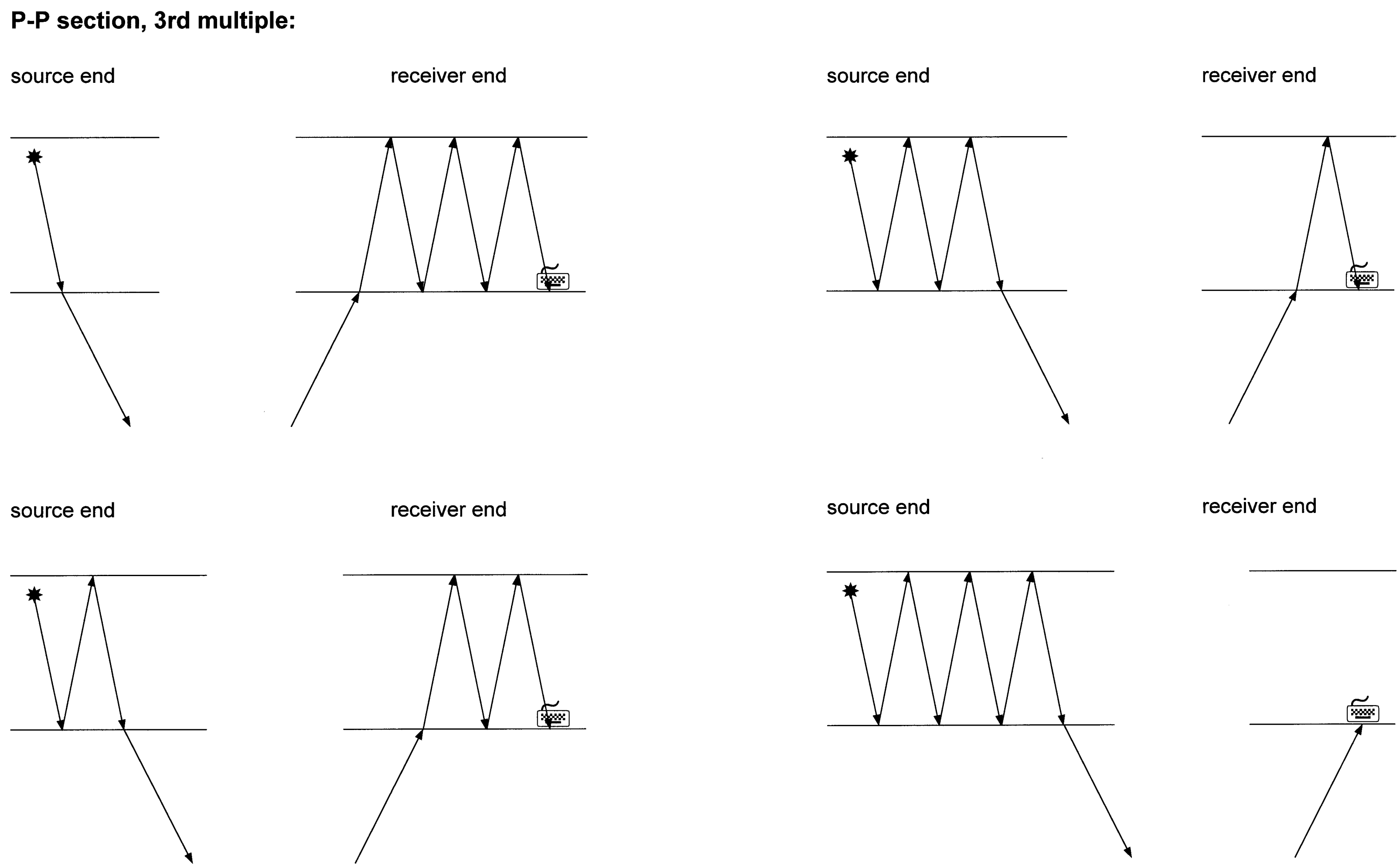



Fig. 5. Sketch showing the $n + 1$ different path combinations contributing to the $n$th-order water-column multiple associated with a primary P-P reflection, for the case of uniform water depth and $n = 3$.

and inline-horizontal geophone (X), assuming isotropy and vertical symmetry. This was done both for incident P and incident S. In doing this, we began with the assumption that water depth is uniform over the survey so that source-end and receiver-end multiples, as well as those travelling on mixed reverberation paths, all arrive in phase at the same time. These multiples will now include contributions arriving both from above and from below (Figures 4 and 5).

## Initial results

Some initial results have been obtained for the second type of water-column multiple, those associated with primaries, and assuming a uniform water depth. These show a wide variation in the amplitude ratio *W/Z* compared with that given by the simple theory, which only considers receiver-end bounces and vertical incidence. Tables 1 to 4 give computed amplitudes for the primary and multiples up to order 5 for various cases. The model used has P-wave velocities of 1480 and 1950 m/s, S-wave velocities of 0 and 1026 m/s, and densities of 1030 and 2200 kg/m$^3$ in the water and the seabed, respectively. The incident primary is assumed to have unit amplitude and losses are taken into account in the computation only for reflection and transmission, that is, not for geometrical spreading or anelastic absorption. This does not affect values obtained for ratios of components, like *W/Z* and *Z/X*.

Table 1. Relative amplitudes recorded on hydrophone (W), vertical (Z) and inline (X) and amplitude ratios for primary and following multiples assuming vertical incidence and receiver-end bounces only.

| Multiple order | *W* | *Z* | *X* | *W/Z* |
|---|---|---|---|---|
| 0 | 1.476 | 1.476 | 0.000 | 1.000 |
| 1 | -2.178 | 0.774 | 0.000 | -2.814 |
| 2 | 1.036 | -0.368 | 0.000 | -2.814 |
| 3 | -0.493 | 0.175 | 0.000 | -2.814 |
| 4 | 0.234 | -0.083 | 0.000 | -2.814 |
| 5 | -0.111 | 0.040 | 0.000 | -2.814 |

Table 2. Relative amplitudes recorded on hydrophone (W), vertical (Z) and inline (X) and amplitude ratios for primary and following multiples assuming vertical incidence and both source- and receiver-end bounces.

| Multiple order | *W* | *Z* | *X* | *W/Z* |
|---|---|---|---|---|
| 0 | 1.476 | 1.476 | 0.000 | 1.000 |
| 1 | -2.879 | 0.072 | 0.000 | -40.064 |
| 2 | 2.405 | -0.402 | 0.000 | -5.980 |
| 3 | -1.637 | 0.366 | 0.000 | -4.467 |
| 4 | 1.013 | -0.258 | 0.000 | -3.933 |
| 5 | -0.593 | 0.162 | 0.000 | -3.659 |

The most dramatic difference between Tables 1 and 2 is in the amplitude of the first-order multiple on the vertical geophone, only about 9% of that given by the simple theory. The two contributions, from source end and receiver end, are of almost the same amplitude but opposite sign and there is considerable destructive interference of the two contributions. The other big difference is in the ratios *W/Z*: in Table 2 this ratio varies greatly so there is no single scaling factor (as there is in Table 1) that will eliminate all orders of multiple.

Table 3. Relative amplitudes recorded on hydrophone (W), vertical (Z) and inline (X) geophones and amplitude ratios for primary and following multiples, assuming P-wave incidence at 15º and both source- and receiver-end bounces.

| Order | *W* | *Z* | *X* | *W/Z* | *Z/X* |
|---|---|---|---|---|---|
| 0 | 1.443 | 1.415 | 0.534 | 1.020 | 2.648 |
| 1 | -2.792 | 0.092 | -0.241 | -30.302 | -0.383 |
| 2 | 2.295 | -0.395 | 0.108 | -5.806 | -3.646 |
| 3 | -1.536 | 0.349 | -0.049 | -4.394 | -7.170 |
| 4 | 0.934 | -0.240 | 0.022 | -3.887 | -10.984 |
| 5 | -0.538 | 0.148 | -0.010 | -3.626 | -15.134 |

Table 4. Relative amplitudes recorded on hydrophone (W), vertical (Z) and inline (X) geophones and amplitude ratios for primary and following multiples, assuming S-wave incidence at 15º and both source- and receiver-end bounces.

| Order | *W* | *Z* | *X* | *W/Z* | *Z/X* |
|---|---|---|---|---|---|
| 0 | -0.411 | -0.381 | 1.928 | 1.078 | -0.198 |
| 1 | 0.777 | -0.042 | -0.860 | -18.568 | 0.049 |
| 2 | -0.610 | 0.113 | 0.384 | -5.410 | 0.294 |
| 3 | 0.389 | -0.092 | -0.171 | -4.226 | 0.537 |
| 4 | -0.226 | 0.060 | 0.076 | -3.782 | 0.780 |
| 5 | 0.124 | -0.035 | -0.034 | -3.550 | 1.021 |

Table 3 shows that the ratio *W/Z* does not vary too greatly from 0º to 15º. It also shows that there are fairly significant amplitudes on the inline geophone as a result of a P wave incident at 15º, both for primary and multiples: for the primary arrival the apparent angle of incidence is 20.7º. In Tables 3 and 4 the values of *W/X* (not tabled) are of the same sign for both primary and multiples, which shows that combining these two components would not be favourable to multiple attenuation. The ratio *Z/X*, however, has opposite sign for primary versus multiples, indicating that combining these two components is a potential strategy for multiple attenuation. However, there would be large problems with this as well, one being that the ratio values vary quite a lot; that is, there is no single scaling factor that would do the job.

Table 4 also shows that there are fairly significant amplitudes on W and Z – even greater on W (the hydrophone) – as a result of an S wave incident from below at 15º. It should be borne in mind that these numbers have been computed for incident P and S waves of unit (the same) amplitude and the same angle of incidence. In reality, incident P-S arrivals may not generally be as energetic as P-P; and, on a given trace, P-S incidence would normally be closer to vertical than P-P, giving rise to lower amplitudes on conversion to P at the seabottom. However the relative effects of a P-S arrival on W and Z would remain the same.

For reverberations confined to the water layer, we expect less divergence from the simple theory as all the water-column energy is arriving from above and it is mainly the assumption of vertical incidence that has to be modified. In fact, because these multiples all arrive from above, they all give the same ratio *W/Z*, in particular all orders of multiple will have the same ratio as for the direct wave from source to receiver, the first arrival for moderate offsets. This raises the possibility of using these first (direct) water-bottom arrivals in the determination of a scaling factor to use in a dual-sensor elimination of virtually all of this type of multiple energy.

## FUTURE WORK

We want to establish just how well the dual-sensor method works with and without various refinements. We hope that modifications to include nonvertical incidence will improve its performance on the reverberations confined to the water layer, which are a big problem themselves (Figure 1). For those water-column multiples associated with primary reflections, a radical modification to the simple method is in order.

As mentioned above, many workers have presented modified methods recently with claims of significant improvement. We would like to examine in detail the most promising of these, perhaps test several of them on a particular trial dataset to compare their effectiveness. Hoffe et al. (1999) indicate the basic soundness of the dual-sensor method and anticipate application of this method, and improved outgrowths of this method, in a CREWES-backed marine OBC survey in the near future in the eastern Canadian offshore.

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