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Fast Deterministic Designature/Demultiple Of 2D And 3D 4C-OBS Data

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Abstract

Four-component ocean bottom seismic (4C-OBS) surveying, in contrast to conventional towed streamer acquisition, records the complete seismic wavefield. When developing seismic processing tools for 4C-OBS data one therefore can liberate one's mind from the line of thought used in the development of seismic processing methodology for streamer seismic. In particular, using the complete wavefield source signature deconvolution and the troublesome problem of attenuation of sea-surface related multiples can be specially designed for 4C-OBS data. The attenuation of these events is an essential prerequisite for an accurate seismic imaging.

In 2001, Amundsen et al. published a fully data-driven method that without any information transforms, during processing in a computer, the recorded 4C-OBS data with the sea surface present into those data that would be recorded in a hypothetical 4C-OBS experiment with the sea surface absent. Removing the sea surface is equivalent to removing all sea-surface related multiples. Further, this method automatically designatures the 4C-OBS data.

Under the model assumption of a layered earth, the designature/demultiple method reduces to deterministic deconvolution where the deconvolution operator is designed from the inverse of the downgoing acoustic field. This assumption, however, does not severly limit the method's practical use in attenuating free-surface related multiples even in geologically quite complex areas. Further, this designature/demultiple scheme is the only method in the class of free-surface demultiple methods that straightforwardly is implemented in 3D for removing free-surface multiples in today's geometries of 4C-OBS surveys. The method, which is numerically fast, is implemented by several seismic contractors. During the presentation we show results of designature/demultiple processing on half a dozen 4C-OBS deep-water and medium-water depth exploration lines.

Introduction

Soon after the introduction of four-component ocean bottom seismic (4C-OBS) technology (Berg et al., 1994a,b; Ikelle and Amundsen, 2004) efforts to develop 2D and 3D wave-equation prestack depth imaging intensified (Amundsen et al., 2000; Arntsen and Røsten, 2002). To obtain accurate and detailed imaging, however, attenuation of multiple energy while preserving the character of primaries is required. Through the 1990's till today one has seen many excellent developments of wave-equation based free-surface demultiple algorithms for 2D and 3D streamer seismic and land seismic data (see, e.g., Fokkema and van den Berg, 1990; Verschuur et al., 1992; Matson and Weglein, 1996; Matson, 1997; Weglein et al., 1997; Ziolkowski et al., 1999; Lokshtanov, 1999; Ikelle, 1999a,b; Ikelle et al., 2003; Kleemeyer et al., 2003; Hokstad and Sollie, 2003). The attractiveness of these methods is that they do not require any information about the subsurface. A possible disadvantage is that these methods require information of the source signature. Further, the streamer-seismic demultiple methods can not straightforwardly be adapted to 4C-OBS data, in particular not for 3D ocean bottom seismic surveys. Amundsen (2001), Amundsen et al. (2001), and Holvik (2003) published an alternative way of removing free-surface multiples in the case that the complete wavefield is recorded in the seismic experiment. For streamer seismic, the complete wavefield on the streamer is the pressure field and the vertical component of the particle velocity (or vertical pressure gradient). For 4C-OBS the complete wavefield is the pressure field and the three components of particle velocity (or acceleration). From the recording of the complete wavefield Amundsen and coworkers posed a solution to the free-surface demultiple problem that does not require any knowledge of the source signature. The essence of the method is to design a demultiple operator from the inverse of the downgoing part of the acoustic wavefield (downgoing pressure or downgoing component of the particle velocity). See Figure 1.

The method has the following additional characteristics: it preserves primary amplitudes; it requires no knowledge of the subsurface; it removes without any information all variations in the water layer; it accommodates source arrays; and no information of the physical source array, its volume, and its radiation characteristics (wavelet) is required. The method thus has a potential for use in time-lapse seismic as any water velocity changes and tidal changes are eliminated. Source designature is an implicit part of the demultiple process; hence, the method is capable of transforming recorded reflection data excited by any source array below the sea surface into demultipled data that would be recorded from any point source (monopole or dipole) with any desired signature (e.g., zero-phase).

In the following we briefly describe the designature/demultiple method, first for an arbitrary earth, and then for a layered earth. Finally, we present two data examples.

Designature/demultiple method for arbitrary earth

Amundsen et al. (2001) derived an integral relationship between the recorded pressure and particle velocity data (p, v_m) in the physical ocean-bottom seismic experiment, containing all free surface related multiples, and the desired designatured multicomponent data with those multiples absent, ($\tilde{p}, \tilde{v}_m$). The desired data are those data that would be recorded in a hypothetical ocean-bottom seismic experiment from a monopole or dipole point source with desired signature $\tilde{a}$ in the case when the water layer extends upward to infinity. The geology below the water layer is the same in the physical and hypothetical ocean bottom seismic experiments.

Assume that the pressure field and the vertical component of the particle velocity (p, v_3) are acoustically decomposed into upgoing (u) and downgoing (d) waves so that the full fields always are the sum of their upgoing and downgoing components, according to

$$p = p^{(u)} + p^{(d)}; v_3 = v_3^{(u)} + v_3^{(d)}$$

The following equation

$$\tilde{a}\cdot v_m(x_r, x_s) = -2i\omega\rho\int dx\tilde{v}_m(x_r, x)v_3^{(d)}(x, x_s)$$

then describes the integral relationship between the field $\tilde{v}_m$ in the hypothetical ocean-bottom seismic experiment, with point source of signature $\tilde{a}$ just above the sea floor and receivers just below the sea floor, and the recorded field and computed downgoing component of the vertical particle velocity just above the sea floor, from a source located at center location x_s. Pressure recordings are processed similarly. The integral relationship for the upgoing part of the pressure fields in the physical and hypothetical experiments are

$$\tilde{a}\cdot p^{(u)}(x_r^-, x_s) = -2i\omega\rho\int dx\tilde{p}^{(u)}(x_r^-, x)v_3^{(d)}(x, x_s)$$

Observe that $(-2i\omega\rho v_3^{(d)})^{-1}$ can be interpreted as a multidimensional operator that acts as (i) a deterministic designature operator, and (ii) a deterministic free-surface multiple attenuation operator. Since frequency domain multiplication by $-i\omega$ corresponds to temporal derivation, the operator is inversely proportional to the time derivative of $v_3^{(d)}$. Note that no information, except location, about the physical source array and its wavelet, and no information of the properties of the water layer above the recording plane has been used to derive the integral equations for $\tilde{v}_m$ and $\tilde{p}^{(u)}$. Hence, the method is independent of volume and geometry of the marine source array and independent of any vertical variations in water layer properties and the state of the sea surface. This property potentially can make the method attractive for processing time-lapse ocean-bottom seismic data.

The integral equations are Fredholm integral equations of the first kind for the desired designatured/demultipled fields, leading to a system of equations that can be solved for $\tilde{v}_m$ and $\tilde{p}^{(u)}$ by keeping the receiver coordinate fixed while varying the source coordinate.

Designature/demultiple method for layered earth

In a horizontally layered medium the seismic response is laterally shift invariant with respect to source location. It then follows that any component of the designatured/demultipled field is obtained by spectral deconvolution between the field itself and the downgoing part of the pressure. In the frequency-wavenumber domain the designature/demultiple of the m th component of the particle velocity reads

$$\tilde{V}_m = \frac{V_m}{P^{(D)}}\tilde{P}^{(dir)}$$

while the designature/demultiple of the pressure recording becomes

$$\tilde{P}^{(U)} = \frac{P^{(U)}}{P^{(D)}}\tilde{P}^{(dir)}$$

where, for a monopole point source,

$$\tilde{P}^{(dir)} = -\frac{\tilde{a}}{2ik_z}\exp(ik_z(z_r - z_s))$$

or, for a dipole point source,

$$\tilde{P}^{(dir)} = -\frac{\tilde{a}}{2}\exp(ik_z(z_r - z_s))$$

is the direct wavefield from the desired source. The phase shift corrects for difference in source and receiver depth levels, and k_z is the vertical wavenumber. Observe that $(P^{(D)})^{-1}$ is the multidimensional spiking deconvolution operator. This designature/demultiple scheme may be implemented as frequency-wavenumber domain or tau-p domain algorithms. In the frequency-wavenumber domain, a joint designature and multiple attenuation process is performed for each combination of frequency and wavenumber. In the tau-p domain, the process is performed for each p-trace. White noise can be added to stabilize the deconvolution. The amount of added white noise can vary as function of slowness.

In today's 3D4C-OBS surveys with dense source-side sampling but coarse cross-line receiver sampling the designature/demultiple method is run on tau-p transformed common receiver gathers. Compared to published techniques for 3D free-surface demultiple for streamer data, this designature/demultiple method is very fast. To our knowledge, this is the only deterministic free-surface demultiple method that directly can be applied to 3D4C-OBS surveys with today's geometries.

Designature/demultiple examples

Seismic plays a significant role in deepwater exploration and development. Despite improvements in seismic data quality, many deepwater seismic challenges remain. The water column causes varying challenges for seismic methods. Currents and tidal changes have an impact on seismic data quality and repeatability. Strong water surface multiple energy often masks the prospective intervals and proves to be a persistent processing challenge. In this paper we present two deep-water data PSDM examples where the layered model designature/demultiple scheme has been applied to solve, in part, the above-mentioned deep-water challenge.

The first example is taken from a 2D4C-OBS line acquired in 1998 in deep-water offshore Norway. Figure 2a shows a limited part of the P-wave migrated stack section when no designature/demultiple is applied. This section serves only as a reference to show the multiple content in the data. The yellow arrow points to the onset of the first water bottom multiple. Beneath this multiple the free surface gives rise to a train of multiple energy that totally destroys any primaries. Next, the P-wave data were processed including the designature/demultiple in the sequence. The multidimensional spiking deconvolution operator is computed from amplitude-frequency and phase-frequency matched pressure and vertical component of particle velocity. The desired source signature (wavelet) chosen is a zero-phase wavelet. The resulting migrated stack section is displayed in Figure 2b. Comparing with Figure 2a, where no designature/demultiple is applied, we observe that primaries which in Figure 2a are masked by multiples are revealed in Figure 2b. In particular, the bright spot in the lower center of the section is clearly defined after designature/demultiple processing. Also, note that whereas the phase of the wavelet is unknown in Figure 2a, the wavelet phase is zero in Figure 2b. The advantages of zero-phasing seismic data are well recognized by the seismic community. The designature/demultiple algorithm zero-phases the multicomponent ocean-bottom seismic data at the geophysicist's option.

The second example is related to the sub basalt imaging challenge in the presence of strong multiples. The data are part of a regional 2D4C-OBS in the West of Shetland/Faeroe area where the water depth increases from 300 to 1400 m along the line. In Figure 3a, PSDM data are shown without any designature/demultiple applied. The yellow arrow points to the onset of the first water bottom multiple. After applying the designature/demultiple process, the multiple train is well attenuated, and primary information revealed as seen in Figure 3b. Figures 4 shows a zoom-up of Figure 3. Now, the yellow arrow in Figure 4a is pointing on a primary that is totally run over by the first water bottom multiple. In Figure 4b, after designature/demultiple, the primary is recovered.

Conclusions

A method for eliminating the effect of the free surface from 3D4C ocean-bottom seismic data has been presented. The method does not need any information about the source array (except location), about the sea floor parameters and the subsurface below the sea floor, about any variations in the water layer from the local density and acoustic velocity, or about the state of the sea surface. Implicitly in the demultiple process is a designature process that removes the source array effect from the recorded data. The data output from the designature, free-surface demultiple process are data that would be recorded from a monopole or dipole point source with desired signature above the same geology as in the physical experiment, but with the free surface absent.

Under certain assumptions, we find that the layered model designature/demultiple scheme works satisfactorily on ocean-bottom seismic data recorded above quite complex geological structures. The P-wave PSDM sections from the ocean-bottom seismic surveys show that the layered model designature/demultiple algorithm increases resolution and provides better reflection continuity by transforming multiple contaminated data with an unknown source wavelet to free-surface demultipled data with a choosen zero-phase wavelet.

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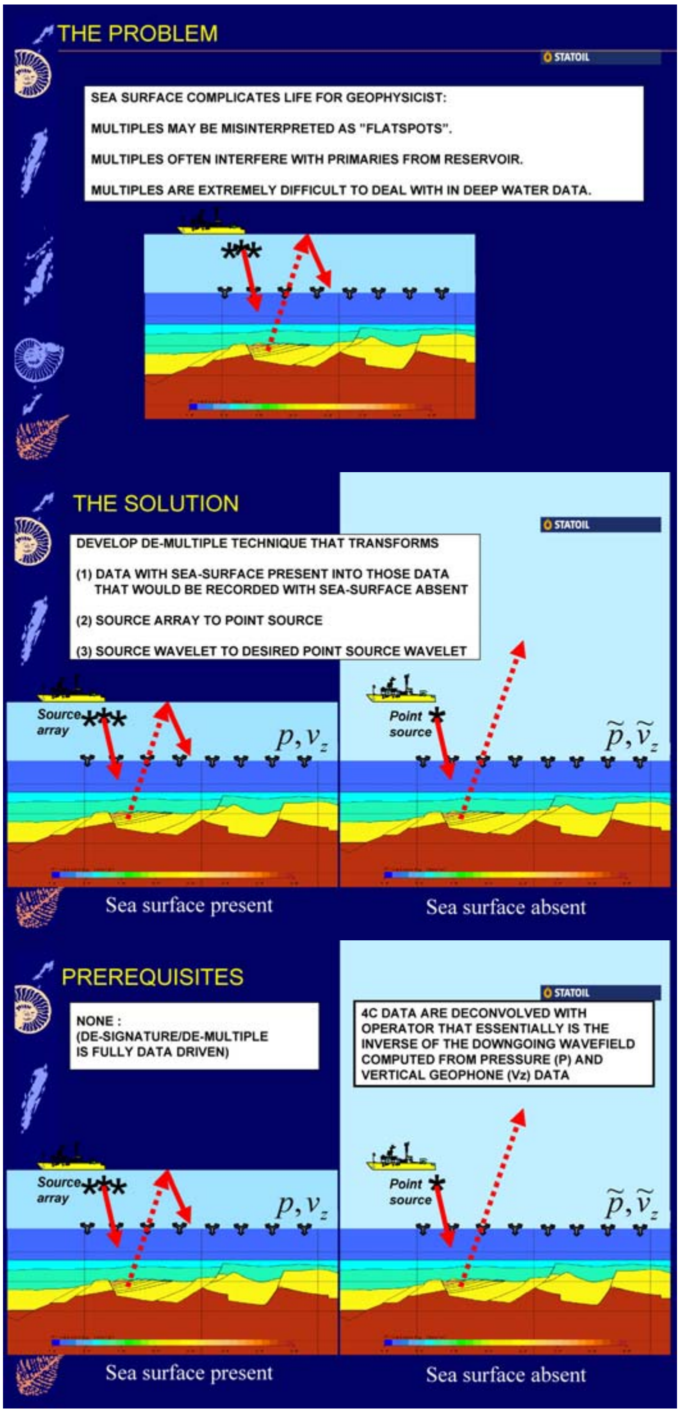


THE PROBLEM

SEA SURFACE COMPLICATES LIFE FOR GEOPHYSICIST:

MULTIPLES MAY BE MISINTERPRETED AS "FLATSPOTS".

MULTIPLES OFTEN INTERFERE WITH PRIMARIES FROM RESERVOIR.

MULTIPLES ARE EXTREMELY DIFFICULT TO DEAL WITH IN DEEP WATER DATA.

THE SOLUTION

DEVELOP DE-MULTIPLE TECHNIQUE THAT TRANSFORMS

(1) DATA WITH SEA-SURFACE PRESENT INTO THOSE DATA THAT WOULD BE RECORDED WITH SEA-SURFACE ABSENT

(2) SOURCE ARRAY TO POINT SOURCE

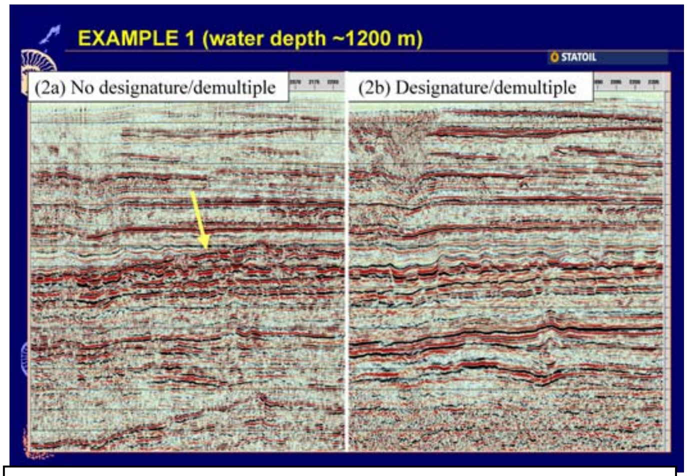
(3) SOURCE WAVELET TO DESIRED POINT SOURCE WAVELET

PREREQUISITES

NONE :
(DE-SIGNATURE/DE-MULTIPLE IS FULLY DATA DRIVEN)

4C DATA ARE DECONVOLVED WITH OPERATOR THAT ESSENTIALLY IS THE INVERSE OF THE DOWNGOING WAVEFIELD COMPUTED FROM PRESSURE (P) AND VERTICAL GEOPHONE (Vz) DATA

Fig.1. The solution to the sea surface problem for 3D4C-OBS data is to apply a deconvolution operator designed from the inverse of the downgoing acoustic wavefield to the recordings. This designature/demultiple process is fully data driven, and requires no information.

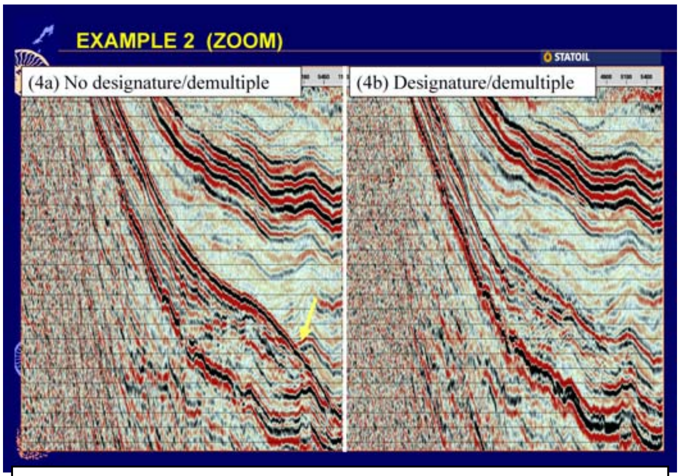


EXAMPLE 1 (water depth ~1200 m)

(2a) No designature/demultiple

(2b) Designature/demultiple

Fig. 2: Data from deep-water area (~1200 m water depth) (a) without designature/demultiple and (b) with designature/demultiple. The yellow arrow is pointing to the onset of the first water bottom multiple, which is dipping upwards from left to right.

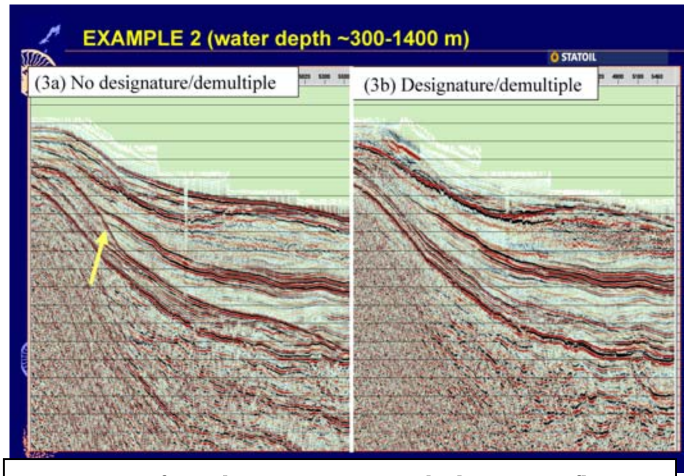


EXAMPLE 2 (ZOOM)

(4a) No designature/demultiple

(4b) Designature/demultiple

Fig. 4: Zoom of data from deep-water area in Fig. 3. The yellow arrow in (a) is pointing on a primary event that gets totally run over by the first water bottom multiple. In (b) after designature/demultiple, the primary is



EXAMPLE 2 (water depth ~300-1400 m)

(3a) No designature/demultiple

(3b) Designature/demultiple

Fig. 3: Data from deep-water area with sloping sea floor (~300-1400 m water depth) (a) without designature/demultiple and (b) with designature/demultiple. The yellow arrow is pointing to the onset of the first water bottom multiple, which is dipping downwards from left to right. Due to clipping of the direct wave on the hydrophone recording the reflectors just below the sea bottom were muted in the designature/demultiple processing.