Summary

Shear wave processing of 3D data requires that the particle motion can be accurately reconstructed from the measurements of the seismic instrument. This requirement cannot be assumed honored on the raw field data: the orientation of the geophones are usually not accurately surveyed, and since the geophone response depends on their largely unknown coupling with the earth, within a single multicomponents sensor the frequency response of each geophone can significantly vary.

We propose a robust method for the QC of the geophones orientations, and a calibration scheme that takes the hydrophone data as a reference to spectrally calibrate each individual geophone.

The methods is illustrated with synthetic example, and applied to real data.

Introduction

In the recent past, manufacturers of the seismic instrumentation have provided the acquisition industry with a new design of geophones that can operate in any direction in space with an identical response. This has the advantage of removing the delicate gimbaled mechanism that was previously incorporated to the cables, and that has been suspected to have originated some of the infidelity in the measurements, due for instance to mechanical resonance when used under operating conditions.

However, the processing of the data cannot be achieved without the accurate knowledge of the actual orientation of the geophones, or alternatively with the projection of the real particle motion on a convenient system such as vertical, radial and transverse. Some authors (Dellinger, et al., 2000) have proposed to find this orientation using the first breaks as they are very energetic signals not affected by other noises. This choice can be questioned though, since the nature of this signal is not clearly defined (direct arrival, refracted waves…), and also because the coupling mechanism with the geophone can be significantly different than that of the reflected and converted energy.

Following previous works (Gratacos, et al. 2002), the converted energy can also be used to implement robust schemes, based on simple 1D modelling for the wave propagation in order to derived post-stack quantities suitable for the reorientation and the spectral calibration of the geophones.

Notations, assumptions on the coupling

The three geophones of a same receiver are tuned by the manufacturer such as vector fidelity is honored. In the absence of mechanical device in the cable, there is no obvious reason why the fidelity should change when the cable is laid out on the sea floor.

However, the shape of the cable and its contact with the earth have a very different aspect in space: an antenna effect can be suspected for the inline direction, and due to gravity (the cable is assumed horizontal), the quality of the coupling of the vertical motion is possibly different than the horizontal cross-line coupling.

Therefore we attach a wavelet to each direction and model the cable coupling by the 3*3 matrix filter:
Single geophone reflectivity estimates

For the estimation of reflectivity quantities, we will consider a general isotropic 1D propagation and model the earth response to shot point p located at constant offset from the receiver:

$$\text{Earth}(p) = R_{pp} Z + R_{iso} U(\theta_p) + R_{trv} V(\theta_p)$$

In this expression, $R_{pp}$ is the earth reflectivity response, $R_{iso}$ the earth conversion response, and $R_{trv}$ a fictitious transverse response.

Based on the N shot points recorded data, we can then estimate those reflectivity quantities for the three geophones. For simplicity, the expressions below are given assuming that the N shots were regularly distributed over a constant offset circle. This assumption is very relevant in the sense that it is the best possible configuration to extract the information from the data, and therefore gives the upper bound of what can be extracted from the dataset. It is also an assumption which is very close to reality as modern sea-bed acquisitions are using a dense regular shot grid. (All real examples were performed without this simplifying assumption).

**Inline geophone Gx:**

- $R_{pp}$: Not recorded
- $R_{iso}$: $w_i = 2/N \sum_p G_{x_p} \cos(\theta_p - \phi)$
- $R_{trv}$: $w_i = 2/N \sum_p G_{x_p} \sin(\theta_p - \phi)$

**1st orthogonal geophone Gy of angle $\psi$ with Z axis:**

- $R_{pp}$: $w_i \cos(\psi) = 1/N \sum_p G_{y_p}$
- $R_{iso}$: $w_i \sin(\psi) = 2/N \sum_p G_{y_p} \cos(\theta_p - \psi)$
- $R_{trv}$: $w_i \sin(\psi) = 2/N \sum_p G_{y_p} \sin(\theta_p - \psi)$

**2nd orthogonal geophone Gz of angle $\psi + \pi/2$ with Z axis:**

- $R_{pp}$: $w_i \cos(\psi + \pi/2) = 1/N \sum_p G_{z_p}$
- $R_{iso}$: $w_i \cos(\psi + \pi/2) = 2/N \sum_p G_{z_p} \cos(\theta_p - \psi)$
- $R_{trv}$: $w_i \cos(\psi + \pi/2) = 2/N \sum_p G_{z_p} \sin(\theta_p - \psi)$

**Geophone orientation**

The direction of the cable is well known from a mere map of the receivers layout. But labeling errors are always a possibility, and the cable can some times have locally an azimuth different to the cable direction:

$$\phi_{\text{real}} = \phi_{\text{field}} + \delta$$

We know that in reality, under the hypothesis of isotropic propagation, the transverse reflectivity doesn’t exist, but we find that $R_{trv} \cos(\psi)$ is estimated by the expression above as $R_{iso} \sin(\delta)$.

For the inline geophone this $\cos(\psi)$ value is 1, therefore minimizing the energy of the transverse reflectivity with respect to the angle $\phi$ gives the most probable cable direction.

This minimisation gives a simple trigonometric equation:

$$Kc \cos(2\phi) + Ks \sin(2\phi) = 0$$

where $Kc$ and $Ks$ are statistical quantities data and source distribution dependant.

**Figure 2. Inline component direction, real dataset.**
A data window around 500-700 msec below seafloor was used, for shots located at 50 to 120m offset. (A better knowledge of the PS velocity field would allow a larger offset selection and remove some of the anomalies due to noise).

Fig 2 above shows that the inline direction can be extracted from the converted data using a shallow window, as the geophones are quite accurately pointing to the receiver next to them.

We have made the assumption that the earth was isotropic to legitimately minimise the transverse energy. If the azimuthal anisotropy is to be included in the earth response, It is no longer possible to minimise the transverse projection.

For the isotropic case, we could have alternatively modeled the earth response with no transverse reflectivity, and compute for which orientation of the geophone (i.e. $\phi$) the difference ($=\text{Emin}(\phi)$) between the observed data and the model is minimised.

Fig 3 below shows the result of such a scan on a synthetic data, having shots only on one side of the geophone hence producing asymmetrical curves.

When the scanned angle reaches the theoretical direction used to compute the synthetic dataset, the amount of removed energy varies from 100% in the absence of noise down to 60% for a signal to noise ratio of 1. In both cases the true orientation of the receiver is indicated.
The same approach can be adapted for a modeling including the PP, PS fast and slow converted reflectivity, which leads to expressions depending on the direction of anisotropy $\alpha$.

However, for each value of $\alpha$, there is an orientation $\phi(\alpha)$ that minimizes the difference to a common value $E_{\text{min}}$ independent of $\alpha$.

In other words, with our approach, it is not possible to find the orientation of the geophones using converted waves if the data window includes area of azimuthal anisotropy.

### Geophone verticality

The estimators $R_{pp}, R_{iso}$ for the geophones Y and Z gives values that are undetermined due to $\psi$, the angle of Y with the vertical axis. Combining the two geophone Y and Z into a composite vertical geophone:

$$G_p(\psi') = \cos(\psi') G_y \cos(\theta_p - \phi) - \sin(\psi') G_z \cos(\theta_p - \phi)$$

gives an estimation of $R_{pp}$ when $\psi'$ has the correct value.

The water surface modeling (Soubaras, 1996) states that the only difference between the pressure field $P$ (as recorded by the hydrophone) and the vertical velocity $V$ (as recorded by the vertical geophone) at the sea floor is the polarity of the down going wave field that has been reflected on the water surface:

$$P = w_h U (1-z) \quad V = w_v U (1+z)$$

$z$ represents the two-way time propagation in the water layer (known), $w_h$ and $w_v$ the hydrophone and geophone wavelets (unknown).

Hence matching the so-called cross ghosted receivers $P (1+z)$ and $V (1-z)$ allows to estimate an operator that converts $w_h$ into $w_v$.

$G(\psi)$ will have a residue of $R_{iso}$ unless $\psi$ corresponds to the real verticality of the geophone. Since $R_{iso}$ and $R_{pp}$ are not correlated, the correlation coefficient (after match) between and $G(\psi)$ $(1-z)$ and $P (1+z)$ will be maximum only for the correct $\psi$. This process can be applied either pre stack or on common receivers stacks.

**Figure 3:** Synthetic dataset: reorientation scan
The curves indicate the percentage of input data modeled as a function of the geophone orientation. For an angle of 35 deg (used for the synthetic generation) this ratio is maximised even if a large amount of noise is added (lower curve).

**Figure 4:** receiver stacks of hydrophone 1st and 2nd orthogonal geophones

**Figure 5:** receiver stacks of hydrophone and composite vertical geophone
In this noisy dataset, the pre-stack calibration fails to completely separate the shear and compression waves. However the vertical geophone has a reduced amount of shear waves, and has gained a wavelet closer to the reference hydrophone.

**Horizontal geophone calibration**

With the knowledge of the verticality of the geophones it is then possible to simply correct for this angle and produce an horizontal component having a wavelet \( w_x \), or apply the calibration filter obtained by the water surface modeling.

If one geophone is nearly vertical, there is obviously no reliable way to obtain an horizontal cross line component with the hydrophone wavelet.

The conversion to a common horizontal wavelet is then performed with the most appropriate shear wave data window, including or not area with azimuthal anisotropy (Gratacos, et al., 2002).

**Conclusions**

The converted energy can be used to find and QC the orientation of the cable, providing no azimuthal anisotropy is included in the data window.

Modelling the contact of the cable with the sea floor instead of assuming that the infidelities are linked to the geophones responses allows the estimation of the verticality of the geophones, and the computation of horizontal cross line and vertical projections.

To do so requires to use the hydrophone data and the modeling of the ghost at the water surface.

**References**


