The effects of marine currents on seismic data

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Summary

The effects of source and receiver motion have been discussed by a number of authors. However, no attention has been paid to the influence of marine currents, which can attain velocities approaching typical seismic shooting speeds. It is argued that such currents may have a significant effect for OBN analysis, 4D surveys and reconciling data shot in opposing current directions. A theoretical basis is introduced that systematically applies Galilean transformations and wave extrapolations to describe the effects of this motion that includes source and receiver motion. The results are completely consistent with the theory of Doppler (1842) and agree with the theory of Hampson & Jakubowicz (1995). Several methods are described to compensate for the distorting effects of these currents.

Introduction

Since sources and receivers typically move several orders of magnitude slower than seismic waves, it had originally been assumed that any motion effects were negligible. However, Dragoset (1988) showed that there is a significant phase effect for moving sources emitting long signatures. This is most noticeable at high boat speeds, frequencies and apparent dips. Hampson & Jakubowicz (1995) presented an exact theory which described the motion effects of both sources and receivers, noting that reciprocity does not hold for moving sources and receivers. They showed that their theoretical formulation was in complete agreement with Doppler (1842) and they described ways to compensate for these effects during the processing. Recently there has been renewed interest in vibratory sources which has spawned further work, for example, Qi & Hilterman (2016) and Guitton et al. (2021).

At normal seismic shooting speeds of, say, 2-2.5 m/s, it is usually considered appropriate to compensate for the effects of motion. To date, it has been assumed that the shooting medium is stationary. However, this is not necessarily a safe assumption. Indeed, marine and fluvial currents are ubiquitous, ranging from steady persistent currents to sporadic, sometimes turbulent currents. The well-known Loop Current in the Gulf of Mexico is, according to NOAA, "traveling at speeds of approximately 0.8 m/s" (Gulf of Mexico Loop Current, 2023). On the NW Shelf of Australia currents of up to 1 m/s exist (Chevron Corporation, 2015). The speed champion of persistent currents is claimed to be the "Gulf Stream" with an average speed of 1.6 m/s and a maximum speed of about 2.5 m/s (How fast is the Gulf Stream?, 2023). There is even evidence that different currents can operate at different depths. Since current speeds can approach or even exceed vessel speeds, we should anticipate that currents will affect seismic data in a somewhat similar manner to source and receiver motion.

In this paper I develop a theory for the effects of currents on seismic data based on systematic application of Galilean transforms and wave extrapolation. It is demonstrated that this theoretical approach is completely consistent with the theory of Doppler (1842). Furthermore, it agrees with the theory of Hampson & Jakubowicz (1995) as current velocities tend to zero. I use this theoretical approach to explore the effects of currents on marine seismic data and find that under certain circumstances currents significantly distort seismic data. Finally, I propose several ways to compensate for these effects.

Theory

Let's begin with a simple motivating example. Consider a stationary medium overlying a medium moving with velocity u. If an impulse is injected at x_s on the boundary, a semi-circular wavefront, centred on x_s, will radiate with velocity, v, into the upper medium. A second semi-circular wavefront will radiate into the lower medium centred on the moving point $x_s + ut$ as depicted in Figure 1.

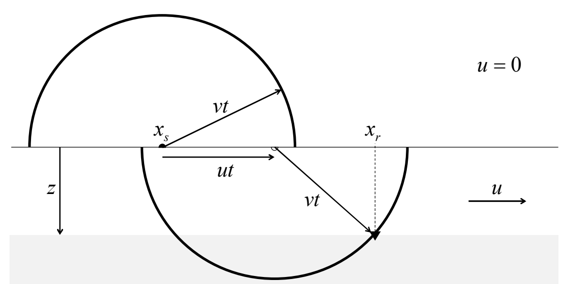

Figure 1: An impulse injected between a stationary and a moving medium. The lower wavefront is displaced by *ut.*

If the lower medium has thickness, z, with a stationary receiver on the bottom at $x = x_r$, it may be shown that the arrival time is given by

$$t = \frac{\sqrt{v^2\left(x_r - x_s\right)^2 + z^2\left(v^2 - u^2\right)} - u\left(x_r - x_s\right)}{v^2 - u^2} . \quad (1)$$

This turns out to be the same configuration that models the direct arrival time at an OBN from a stationary impulsive source in a current moving with velocity u. We can evaluate how the current affects the arrival time. Let us explore the exaggerated case of $u = 500$ m/s for illustration alongside a more realistic case, $u = 1$ m/s . With v=1500 m/s, z=1000 m and x_r=0, the results are shown in Figure 2. The arrival is horizontally sheared with the apex displaced by $-uz/v$. The arrival time at 2000 m offset is ~1 ms different to the stationary case. This is significant for adjustments such as OBN location, clock timing and geophone rotation that rely on direct arrival timing. The effect would be compounded if it had to be reconciled with a second source line acquired in a reversed current direction or comparing 4D surveys acquired under differing current conditions. This simple example shows that there is an effect that deserves investigation.

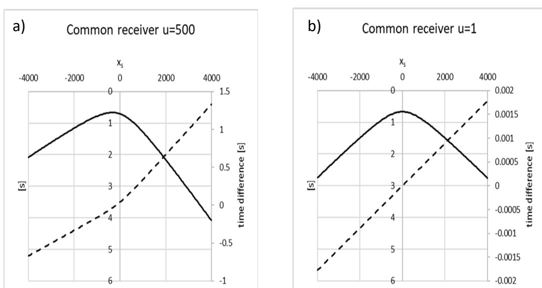

Figure 2: The direct arrival time at an OBN taking the current into account. a) The exaggerated case of u=500 m/s. b) A realistic case of u=1 m/s. The dashed line shows the time difference from u=0.

Galilean Transforms

Galilean transformations are used to map a space-time event between two inertial reference frames, $\mathbf{O}$ and $\mathbf{O}'$, which differ only by the constant *relative* motion between them. They are based on Newtonian physics, assuming time and space are absolute. Our discussion is limited to 2-dimensional space-time for simplicity, however, extension to higher dimensions naturally follows. It is usually assumed that the coordinates coincide at $t = 0$ and that only relative motion takes place. If u is the velocity of $\mathbf{O}'$ w.r.t. $\mathbf{O}$ then the Galilean transformation is given by

$$\begin{bmatrix} x' \\ t' \end{bmatrix} = \begin{bmatrix} 1 & -u \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ t \end{bmatrix}. \qquad (2)$$

This is a shear transform mapping an event at x in $\mathbf{O}$ to x' in $\mathbf{O}'$, an apparent shift of $-ut$. In terms of a wavefield, this says, that $p(t,x') = p(t,x) * \delta(x+ut)$ which is a time variant spatial shift in the *opposite direction* of u. We may consider seismic sources, marine currents, the earth and seismic receivers to all be inertial reference frames. Therefore we may use equation (2) to relate the wavefields in these adjacent inertial reference frames. Let us begin by showing that source and receiver motion using this approach is identical to Hampson & Jakubowicz (1995).

Source motion

A source moving at u_s w.r.t. the water will be remapped by the Galilean transform from the moving source reference frame to the stationary water reference frame as $x_s = x_s' + u_s t$, an apparent time variant shift of $+u_s t$, in agreement with Hampson & Jakubowicz (1995).

Receiver motion

A wavefield in stationary water will be remapped to a receiver moving at u_r w.r.t. the water by the Galilean transform from the stationary water reference frame to the moving receiver frame as $x_r = x_r' - u_r t$, an apparent time variant shift of $-u_r t$, again in agreement with Hampson & Jakubowicz (1995).

The goal now is to describe a systematic model for seismic acquisition that includes currents. The source side and the receiver side will be described separately and for brevity we omit free-surface effects.

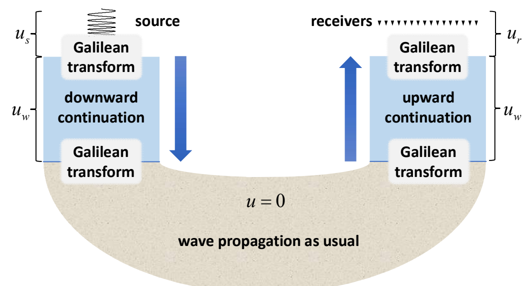

Figure 3: A systematic model for moving sources, receivers and marine currents.

Source-Water-Earth System

What is the effective source just below the seabed in a stationary earth? Although any number of horizontally stratified current layers might be included, we will assume for brevity that there is a single moving body of water. We have the tools to move between inertial reference frames, however, we also need to incorporate wave propagation across the water layer. One choice is to use the 1-way wave equation to depth extrapolate the time dependent wavefield through the water inside the inertial co-ordinate system of the moving water. That, along with the Galilean transforms, completes the left-hand side of the system shown in Figure 3. The source signature undergoes transformation into the moving water layer, that wavefield is downward continued to the seabed, where it undergoes another transformation to place the wavefield in the inertial frame of the stationary earth. This wavefield is the effective source. Figure 4 illustrates the source-water-earth system using u_s=0, u_w=500 m/s, z=500 m and v=1500 m, for a vibratory source and the exaggerated motion with a) being the signature at the source, b) being the signature after transformation to the moving water reference frame, c) is the wavefield just above the seabed and d) is the wavefield just below the seabed. In this case the Doppler shift is absent in d) but note the displacement of $+uz/v$ and the asymmetric dips which are the effects of the current. The swept signature is to show any Doppler effects.

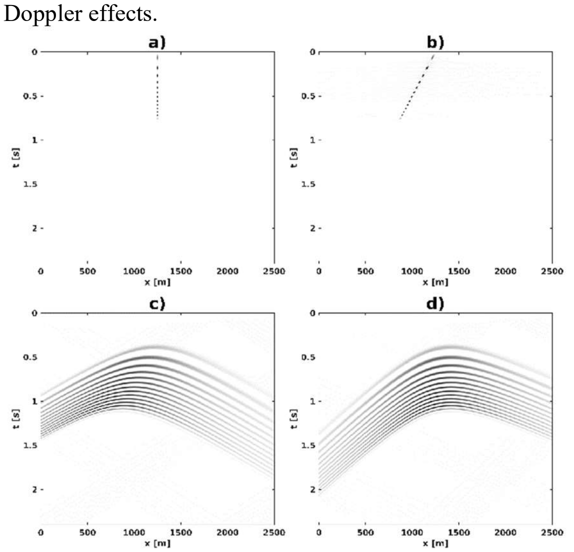

Figure 4: The steps in the source-water-earth system: a) a vibratory source signature, b) the signature in the water, c) the source wavefield just above the seabed, and d) the wavefield just below the seabed; the effective source signature.

Earth-Water-Receiver System

Given an upgoing wavefield just below the seabed, the wavefield recorded at the receivers may be calculated as follows: The wavefield undergoes transformation to the moving inertial frame of the water, this is then upward continued to the depth of the receivers where it undergoes a second transformation into the inertial frame of the receivers. This sequence is depicted in the right-hand side of Figure 3.

Figure 5 illustrates the source-water-earth system using u_r=0, u_w=500 m/s, z=500 m and v=1500 m/s, with a) being a trace in the earth, b) being the trace after transformation to the moving water reference frame, c) is the wavefield in the water adjacent to the streamer and d) is the wavefield recorded by the streamer. In this case, once more, the Doppler shift is absent in d) but note the displacement of $+uz/v$ and the asymmetric dips which are the effects of the current. The trace used was a random band-limited signal. These two examples are simply intended to illustrate the steps. Clearly a stationary streamer or vibrator is unusual, however, by only having the water moving, the effects of the current can be shown in isolation. In both cases the wavefield is asymmetric and displaced. The displacement is proportional to water depth and current speed, and so of more significance in deep water with stronger currents. The effects will be compounded if two adjacent profiles were acquired in opposing current directions.

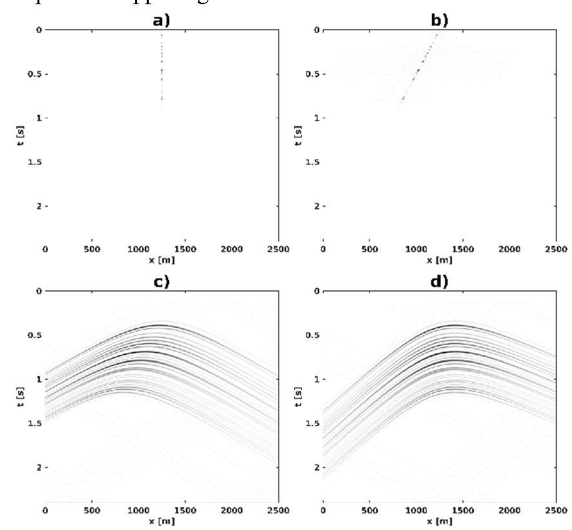

Figure 5: The steps in the earth-water-receiver system: a) a trace in the earth, b) the trace in the water, c) the wavefield adjacent to the streamer, and d) the wavefield recorded by the streamer.

The systematic approach described above works with time dependent waveforms and depth extrapolation. An alternative approach is to use finite difference propagation of space dependent waveforms extrapolating in time with a modification to the wave equation that has the effect of displacing the wavefield in the moving regions by $u\Delta t$. The advantage of such an approach is that water-layer multiples would be accommodated.

The Doppler effect

It may be shown that there is a Fourier equivalent to Galilean transforms (e.g., Drake & Purvis, 2014) which is sometimes called the *shear theorem* (Bracewell, 1986). Using Claerebout's (1985) Fourier kernel, this says that the equivalent Fourier domain Galilean transform is

$$\begin{bmatrix} \omega' \\ k_x' \end{bmatrix} = \begin{bmatrix} 1 & -u \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \omega \\ k_x \end{bmatrix}. \qquad (3)$$

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This is a shear transform mapping an event at ω in $\mathbf{O}$ to ω' in $\mathbf{O}'$; an apparent frequency shift of $-uk_x$. In terms of a wavefield, this says, that $P(\omega',k_x') = P(\omega,k_x) * \delta(\omega + uk_x)$ which is a wavenumber variant temporal frequency shift in the *opposite direction* of *u*. This is the Doppler (1842) effect noted by Hampson & Jakubowicz (1995). It is important to emphasise that u is the velocity of $\mathbf{O}'$ w.r.t. $\mathbf{O}$. The depth extrapolation of wavefields using a one-way wave equation is easily performed in the *f,k_x*-domain by multiplication with $\exp(ik_z z)$ (Claerbout, 1985). We can write the systematic model in the Fourier domain symbolically as

$$L_{r|w} e^{ik_z z} L_{w|e} R L_{e|w} e^{ik_z z} L_{w|s} S , \qquad (4)$$

in which $L_{b|a}$ is the Fourier Galilean transform (3) from *a* to *b*, R is the solid earth's impulse response and S is the source signature. It being understood that (4) should be evaluated right-to-left. Temporal and spatial frequencies are not changed by $\exp(ik_z z)$ and the Galilean transform does not change spatial frequencies. However, the earth's response typically changes spatial frequencies due to scattering and heterogeneity. As a result, the effects of the system need to be split into the incident (effective source) side and reflected (effective receiver side). Using the notation of (4), the source and receiver sides are respectively

$$L_{r|w} L_{w|e}, \quad L_{e|w} L_{w|s} . \qquad (5)$$

Evaluating (5) for the frequency entering the earth and the frequency recorded at the receiver respectively, we find that

$$\omega_e = \omega_s + u_s k_s, \quad \omega_r = \omega_e - u_r k_e , \qquad (6)$$

which has assumed that $u_e = 0$. The subscripts indicate in which reference frame the variables apply. As far as the Doppler shift is concerned, (6) shows that <u>the current has no effect</u>. Since on the receiver side, $k_e = k_w = k_r$ we may replace the second of equations (6) with

$$\omega_r = \omega_e - u_r k_r . \qquad (7)$$

Noting that

$$k_s = \omega_s p_s, \quad k_r = \omega_r p_r , \qquad (8)$$

in which $p = \partial t / \partial x$ w.r.t. to the relevant inertial frame, we may write

$$\omega_e = \omega_s (1 + u_s p_s), \quad \omega_r = \omega_e / (1 + u_r p_r) . \qquad (9)$$

Substitution of the first into the second shows that

$$\omega_r = \omega_s \frac{1 + u_s p_s}{1 + u_r p_r} , \qquad (10)$$

which is the Doppler effect for a moving source and receiver consistent with Doppler (1842) and Hampson & Jakubowicz (1995).

Compensating for the effects of motion

There are a number of ways to compensate for the effects caused by the motion of the sources, receivers and the currents. One approach is to perform common shot migration taking the motion into account. In this approach, the migration includes the source signature in the forward source propagation and a 2-way wave equation (acoustic or elastic) that accommodates a moving reference frame. This has the advantage that it could also be used in least squares migration or full waveform inversion and in principle it accommodates multiples.

However, since the Doppler effect is solely due to the source and receiver motion, those distortions may be compensated in exactly the manner described by Hampson & Jakubowicz (1995) as a first step. In doing so there remain distortions due to the currents, that is, the displacement and asymmetry in the wavefields noted in Figure 4d and Figure 5d. The source side is a deconvolution problem using the effective source wavefield (Figure 4d), while the receiver side may be resolved by applying the adjoint of the receiver side model, $\left(L_{r|w} e^{ik_z z} L_{w|e}\right)^{\mathrm{H}}$. The adjoint is chosen because the inverse of the wave extrapolator is a growing exponential.

Conclusions

A theoretical model for the inclusion of marine currents into the motion effects on seismic data has been presented. It has been shown that currents distort the seismic wavefield, however, it has been found that they do not contribute to the Doppler shift, rather, they displace and shear the wavefield. On the source side this means that at the seabed a modified *effective* source wavefield, which is displaced and asymmetric, propagates into the solid earth. On the receiver side the received wavefield is also similarly displaced and asymmetric. The displacement for each side is $u_w z / v$ where z is the water depth. The apparent velocity asymmetry asymptotes to $\mp v + u_w$. Two approaches have been proposed to compensate for these effects both using modified wave equations, one incorporates the corrections proposed by Hampson & Jakubowicz (1995). Finally, it has been demonstrated that this new theory is completely consistent with Doppler (1842) and Hampson & Jakubowicz (1995).

It is worth commenting that although airguns have conventionally been considered to be stationary sources, the overwhelming drag forces from a current moves the bubbles laterally with the current velocity. Bubbles are moving sources.

Acknowledgements

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