The effect of the Fresnel zone size on AVO analysis of CMP gathers

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ABSTRACT

Reflection energy from a linear reflector comes from an aperture often described by the Fresnel zone. Within the Fresnel zone, the diffraction energy constructively builds the reflection. Energy from the edge of a reflector combines to produce a diffraction that distorts the reflectivity amplitudes. Similarly, reflection energy from a target that is smaller than a Fresnel zone will also have distorted amplitudes that violate the requirements for amplitude versus offset (AVO) analysis.

Diffraction theory is presented to evaluate the reflection amplitudes from small targets and from the edges of reflectors.

INTRODUCTION

Geophysicists commonly identify the spatial extent of a reflection with the size of the reflector. However, diffraction energy smears the size of a reflector over an area that is often described by the size of the Fresnel zone. The Fresnel zone is that portion of a reflector from which reflected energy can reach a detector within the first one–half of the reflection.

The geometry for calculating the radius of the first Fresnel zone is well known and is shown in Figure 1. For a coincident source and receiver and constant velocity, the Pythagorean theorem gives

$$(z+\lambda/4)^2 = z^2 + R^2 \tag{1}$$

where z is the reflector depth, λ the wavelength, and R the radius of the first Fresnel zone. Solving for R gives,

$$R = \sqrt{\lambda z/2 + \lambda^2/16}\,. \tag{2}$$

The λ^2 term is usually small enough (relative to the depth) to be neglected. This can also be expressed in terms of the two–way vertical traveltime t_0, velocity v, and wavelet period τ by using the familiar relationships $z=vt_0/2$ and $\lambda=v\tau$. Thus,

$$R = (v/2)\sqrt{t_0\tau} \tag{3}$$

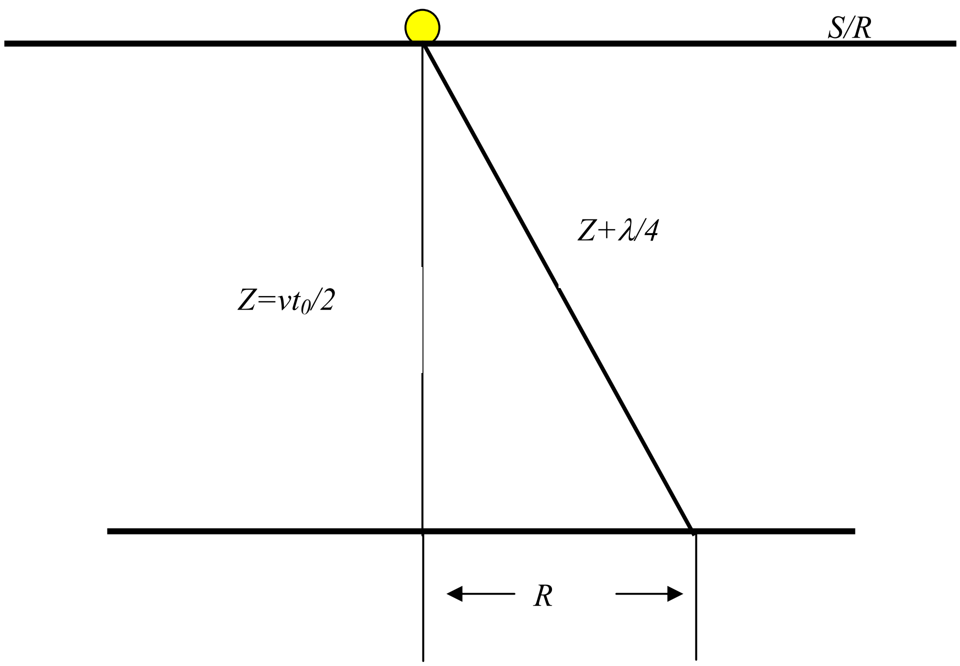
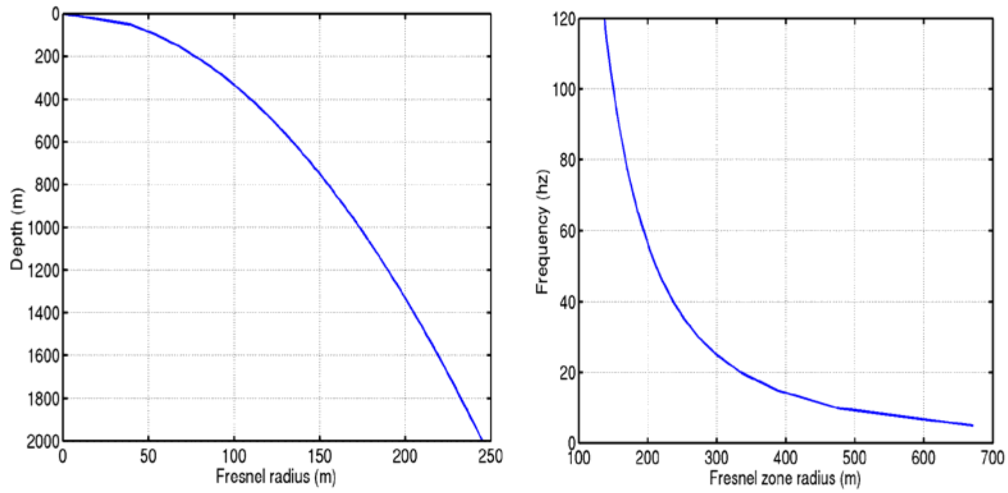


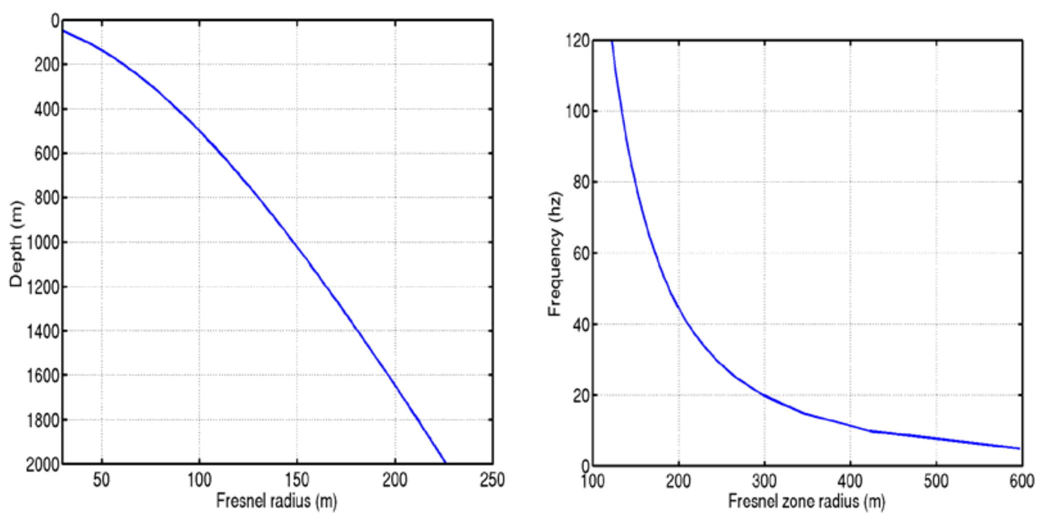
FIG. 1. Geometry for calculating radius of the Fresnel zone.

Figure 2 shows the size of the Fresnel zone radius for a constant velocity of 3000m/s. Part a) shows the size for a constant frequency of 50 Hz and varying depth and b) for a constant depth at 1500m and varying frequency. Similar results are shown in Figure 3, where the velocity increases linearly with depth, (v= 1800+0.5z); a typical approximation for a classic tertiary sedimentary basin.



a) b)

FIG. 2. Fresnel zone radius varies with a) depth and b) frequency for a constant velocity.



a) b)

FIG. 3. Fresnel zone radius varies with a) depth and b) frequency for a variable velocity.

Amplitude analysis within the Fresnel zone for stack data

The reflection energy from reflectors close in size to the Fresnel zone produces amplitudes that differ from larger reflectors. The same effect is observed on reflections that are close to the edge of a reflector. These amplitude changes prevent accurate AVO analysis in areas in which the size of the reflector is similar or less than the size of the Fresnel zone. We will use diffraction theory to evaluate the amplitudes for the 2D zero-offset case.

Diffraction response at the edge of a plane reflector

According to diffraction theory (Berryhill, 1977), the diffraction amplitude at zero–shot geophone distance due to the termination of a planar reflector can be calculated by convolving the reflection wavelet with a time–domain operator called the normalized diffraction response. The diffraction response D_0 at zero-offset can be written in the forms:

$$P_n(t) = f(t) * D_0(t) U(t - t_e) \tag{4}$$

$$D_0(t') = \frac{\cos\theta_0}{\pi} \frac{t_e^2}{(t' + t_e)^2} \frac{d}{dt'} \arctan \frac{\sqrt{t'(t' + 2t_e)}}{t_e \sin\theta_0} \tag{5}$$

in which:

t_e, is the minimum two-way traveltime to the edge of the reflector,

t' the time measured after onset time of the diffraction time t_e, i.e., $vt' = t - t_e$,

θ_e is the angle between the normal to the reflector and the raypath of the minimum traveltime to the edge of the reflector,

f(t) is the source wavelet function, and

$U(t-t_e)$ the unit step function to maintain zero value prior to t_e.

When using equation (5), the D_0 operator calculation requires knowledge of only two parameters, t_0 and θ_0. In practical applications, D_0 is evaluated numerically, with t' defined at discrete time sample. The derivative term in equation (5) then becomes a difference equation that is suitable for digital convolution with a seismic wavelet.

When θ_0 is 0 degrees, D_0 is a one–sample spike with a magnitude equal to exactly one–half. Convolving this spike with any wavelet reproduces the wavelet with one–half its original amplitude. As θ_0 increases, the distance from the source-receiver to the edge of the reflector increases, and the height of the initial peak decreases quickly. When the source and receiver are sufficiently far away from the edge of the reflector, the amplitude distortion can be ignored. That distance is related to the Fresnel zone.

Diffraction modelling

The reflection energy can be considered as the sum of energy from scatterpoints that are located along the reflector. The reconstruction of this energy requires that spacing between the scatterpoints be less than δx that is defined by

$$\delta x = \frac{V}{4f \tan\theta}, \tag{5}$$

where V is the velocity of the medium, f the maximum frequency, and θ the apparent dip of the seismic data. Figure 4 contains a few images of modelling with diffractions that starts in a) with diffraction from each sample in a trace. The amplitude of diffraction is scaled by the amplitude of the sample. The number of traces that produce diffractions is increased until all traces are fully modelled. When all samples on all traces are modelled with diffractions, only the specula diffraction energy and their true diffractions remain. Elsewhere, the energy of the modelling diffractions cancels.

2D reflector model

Trorey, in 1970, also created a 2D model to evaluate the edge effects of diffractions at the edge of the reflector. At that time he identified three cases that require investigation.

1. The reflector size is smaller than the Fresnel zone;

2. The reflector size is equal to the Fresnel zone;

3. The reflector size is larger than the Fresnel zone.

We will follow his example and illustrate the effects on the reflection amplitude for various sizes of reflectors using the diffraction theory of Berryhill (1977) and with diffraction modelling.

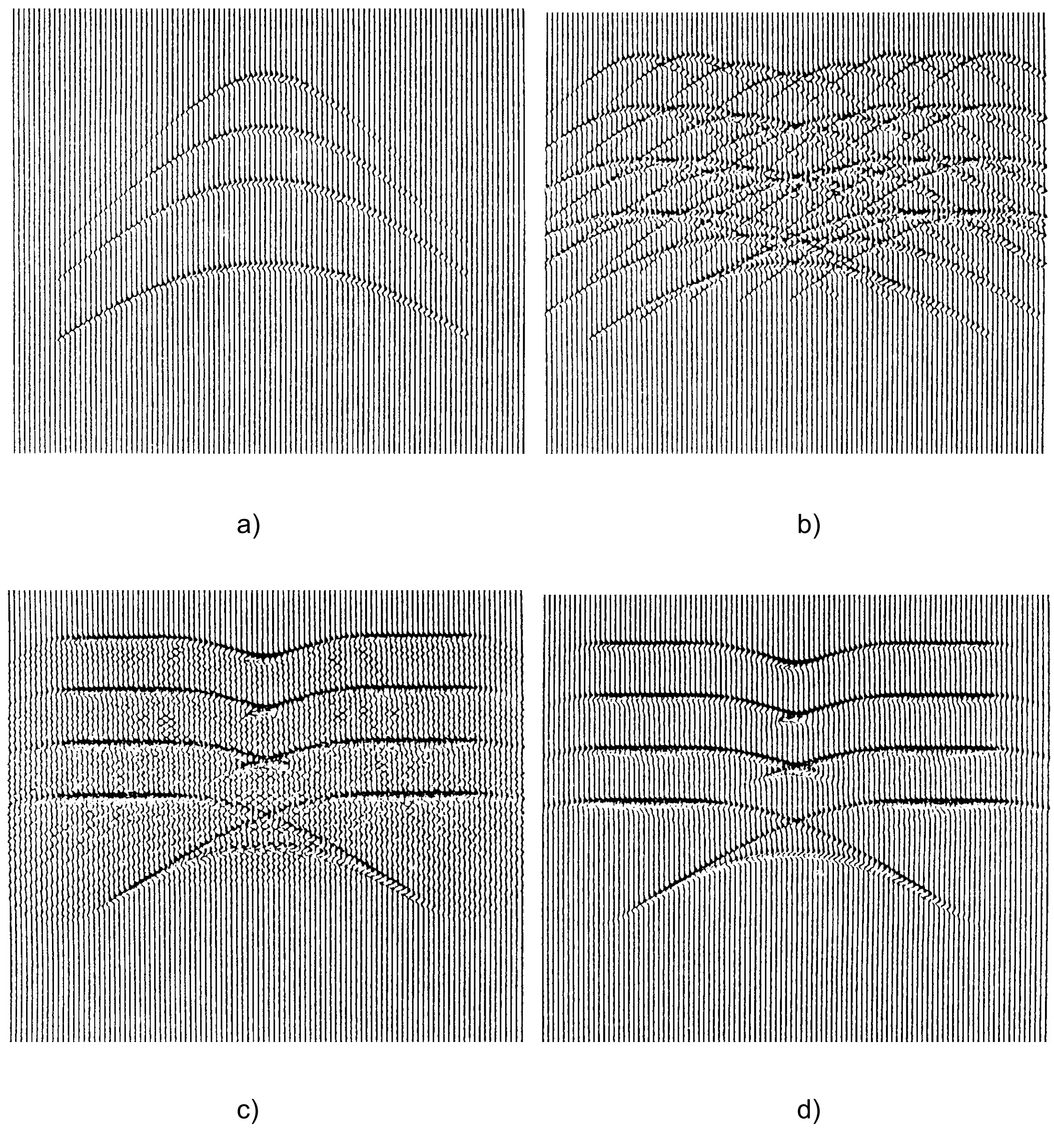


FIG. 4. Diffraction modelling that starts in a) with diffractions drawn for all samples on one trace, b) the diffraction from 8 traces, c) 32 traces, and d) all traces.

MODELLING RESULTS

Modelling based on Berryhill (1977) as discussed above will be presented first. Various source wavelets will be convolved with the computed diffraction response. Following these result some examples of diffraction modelling will be presented. Reflector size is smaller than the Fresnel zone

The amplitude of the edge effect is greatest when the reflector is smaller than the Fresnel zone, as contained in Figure 5. The peak amplitude of the reflection is displayed in Figure 6.

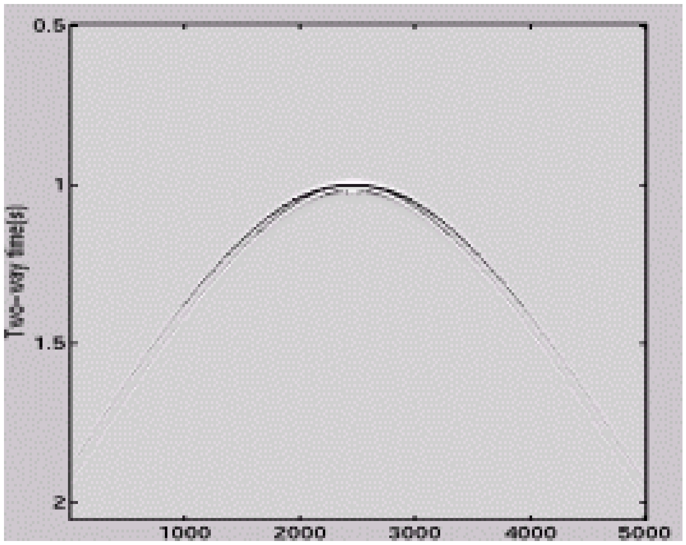
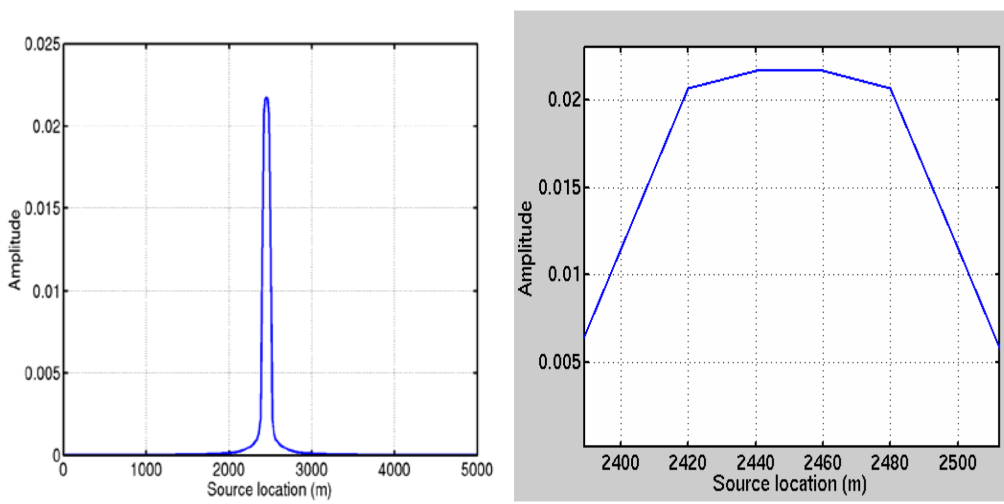


FIG. 5. Reflected and diffracted responses of reflector assuming source along the surface.

It is hard to tell if this reflection is from a diffraction point or a reflector. Thus, when the reflector is smaller than the Fresnel zone, the spatial resolution is lost. In this case, not only is the response smeared but also the amplitude response is neither reflection nor diffraction. The amplitude response at the centre will be smaller than that of a complete reflector. AVO analysis in this case will be ineffective.



a) b)

FIG. 6. The amplitude response of a reflector smaller than the Fresnel zone. a) Amplitude in total; b) zoomed section.

Reflector size is equal to the Fresnel zone

When the size of the reflector is equal to the size of the Fresnel zone, the edge is further from the centre when compared to the previous case. Figure 7 demonstrates that the size of the reflector can be estimated from the size of the reflection. However, the amplitudes above the reflector are still distorted by the edge effects.

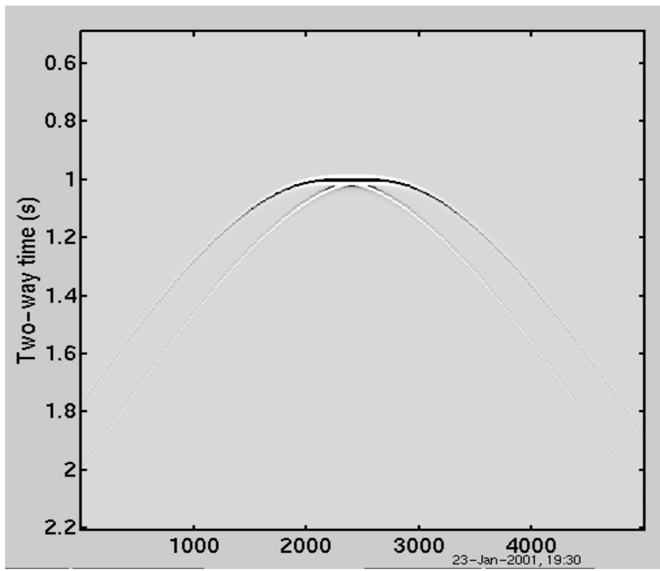
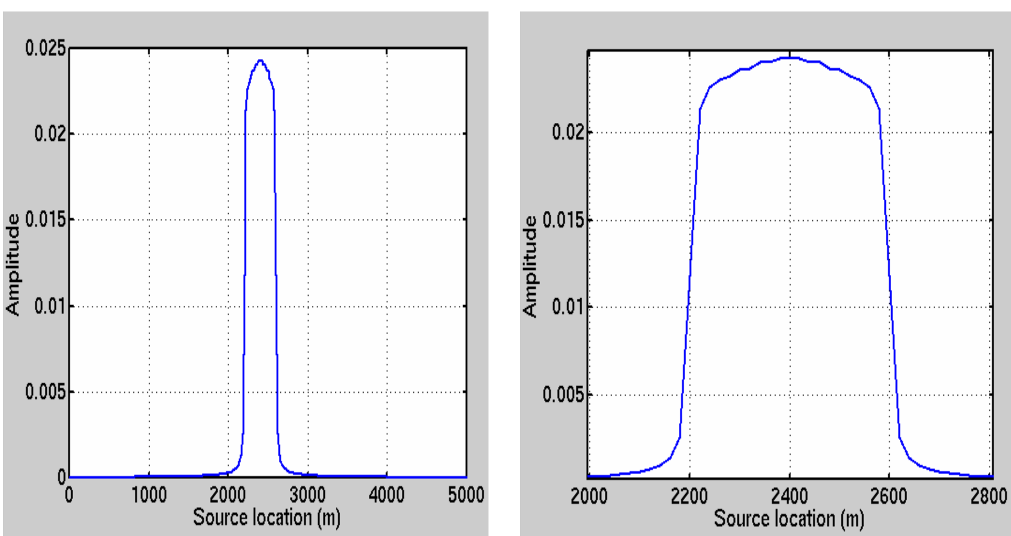


FIG. 7. Response of reflection when the size of the reflector equal to the size of the Fresnel zone.



a) b)

FIG. 8. The amplitude response of the reflector equal to the Fresnel zone. a) Whole view; b) zoomed view.

The reflection amplitudes for Figure 7 are shown in Figure 8. Note the amplitude is still rising in the centre of the reflection. The amplitude response in this case also reveals that AVO analysis will be incorrect if the target zone is equal to the Fresnel zone size.

Reflector size is larger than the Fresnel zone

In most cases, the reflector in the subsurface is larger than the Fresnel zone but caution is still required in areas that are close to the edge. Recognition of the response near the edge of the reflector is important when AVO analysis is performed before migration. The reflection for a reflector that is larger than the Fresnel zone is shown in Figure 9.

The amplitude response of the reflection in Figure 9 is shown in Figure 10. Now we can see that the amplitude in the centre of the reflection becomes stable. The distance at which the amplitude becomes stable is a Fresnel zone distance from the edge. Amplitudes closer to the edge will be distorted. Now, AVO analysis can be performed in the central area of the reflection, at least a Fresnel zone away from the edge.

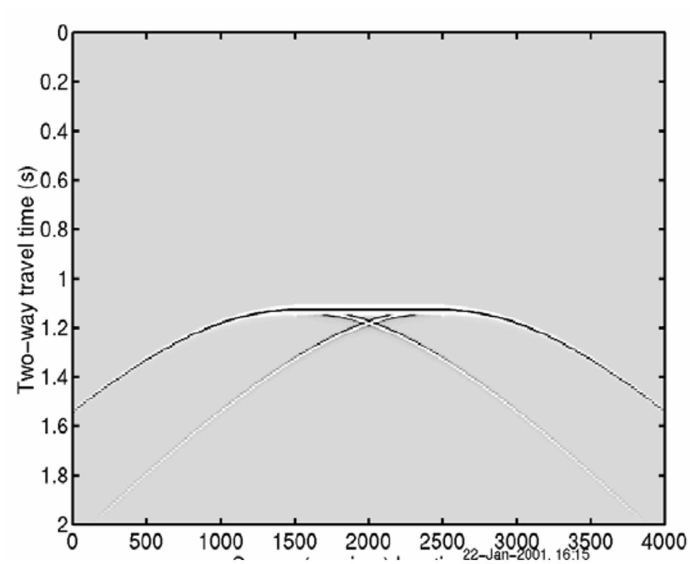
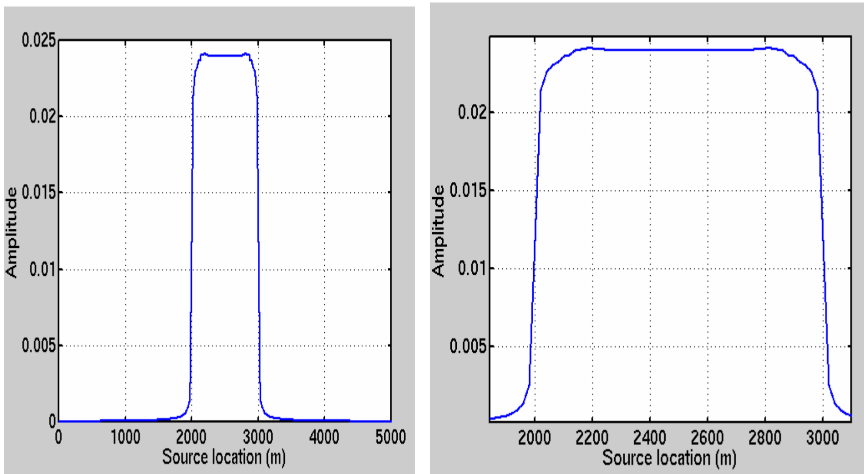


FIG. 9. Response of the reflector larger than the Fresnel zone.



a) b)

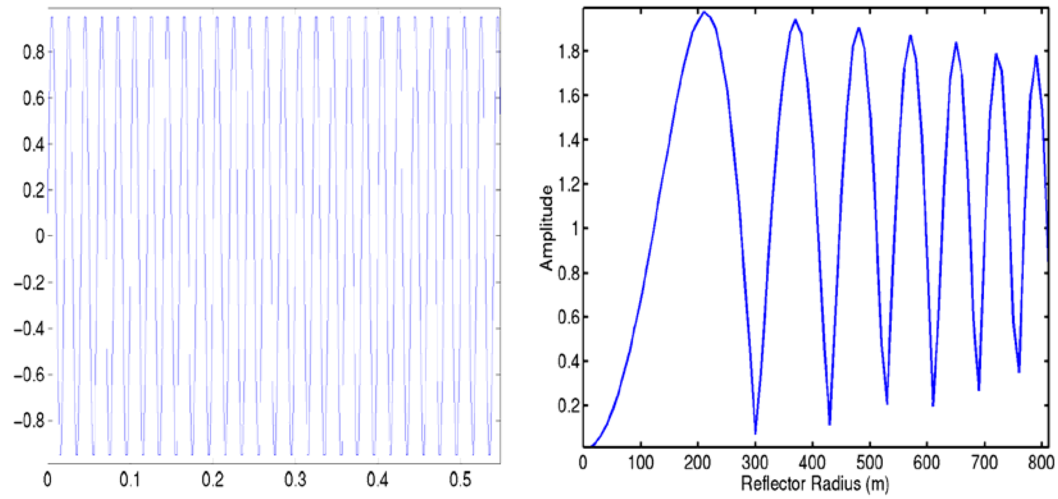
FIG. 10. Amplitude response of a reflector larger than Fresnel zone. a) The whole response, and b) the zoomed view.

VARYING THE NATURE OF SOURCE THE WAVELET

Three types of source wavelets will be considered with the Berryhill method of analysis. The first is a mono-chromatic source, typical of experiments in physics; second, a finite length Ricker wavelet, and third, a band–limited source with a ringy wavelet. These wavelets were convolved with the Berryhill response from a terminated reflector.

Monochromatic source

A mono-chromatic source of Figure 11a was applied to the model and the amplitude response plotted in b). This source is typical in optic experiments, but does illustrate the potential ringing of the Fresnel zones. Previously we have only considered one Fresnel zone, but we can see from Figure 11b that multiple Fresnel zones can occur. We would normally define the Fresnel radius as the distance to the first peak.



a) b)

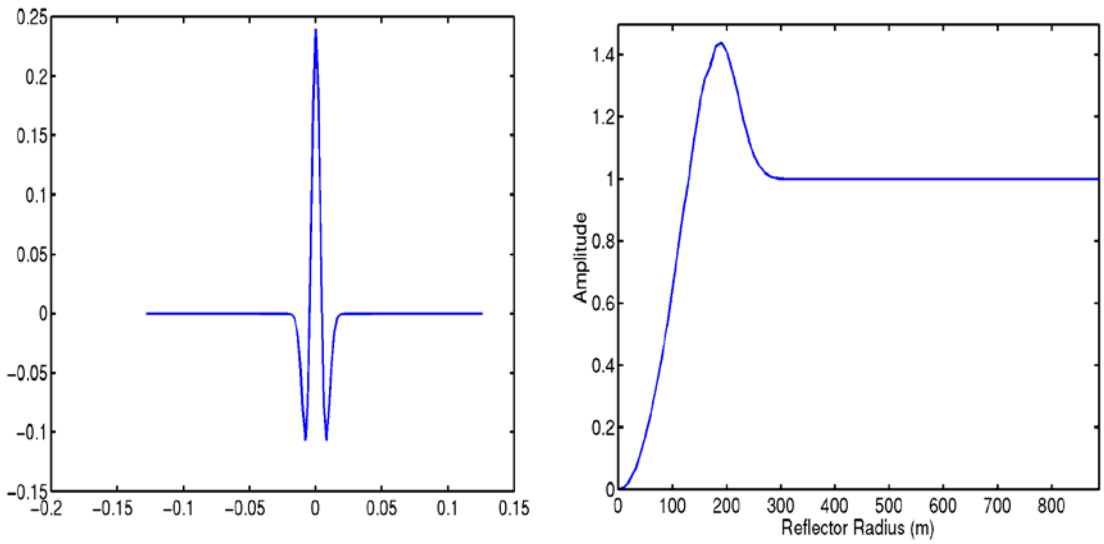
FIG. 11. A monochromatic source in a) and in b) the amplitude response across the reflector.

Ricker wavelet

The Ricker wavelet shown in Figure 12a was convolve with the model and produced the amplitude response in b). Note how soon the amplitude response stabilizes to a constant value. AVO analysis could be conducted at a distance that is slightly larger than the Fresnel zone.

Band–limited wavelet

A band–limited wavelet (not shown) was used as the source for this last demonstration. The time domain wavelet is ringy and is evident on the amplitude response in Figure 13. A comparison of Figures 12b and Figure 13 illustrate that the type of wavelet can increase the edge effect at a considerable distance past the Fresnel radius making AVO analysis difficult.



a) b)

FIG. 12. A Ricker wavelet source in a) and in b) the amplitude response across the reflector.

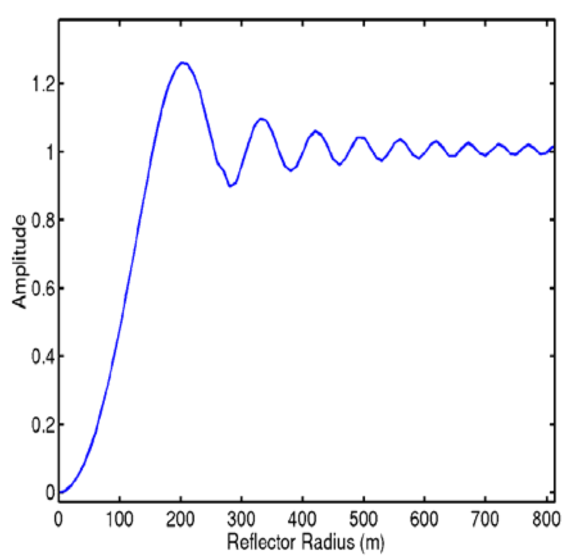


FIG. 13. A band-limited source produces a ringing amplitude response.

Diffraction modelling

A few examples of diffraction modelling have been included to illustrate its potential use in evaluating the size of the edge effect. Each diffraction has amplitude scaling proportional to T_0/T where T_0 is the time at the peak of the diffraction and T the time at any point on the diffraction. This amplitude scaling is compatible with 3D amplitude spreading, but recorded along a 2D line. After the diffractions are defined, the section was filtered with a trapezoidal filter. Some of the figures contain an indication of the peak amplitude along teach trace. These amplitudes are inserted as spikes on the trace at times proportional to the peak amplitude on that trace. The maximum amplitude of the section is scaled to maximum time.

Figure 14 contains a single diffraction to illustrate its shape and amplitude. Note the gradual change in amplitude, especially when compared with the edge diffractions on following figures. Figure 15 shows the reflection from a reflector that is larger than the Fresnel zone. High amplitude is used to display the effects of the wavelet. Where is AVO analysis valid?

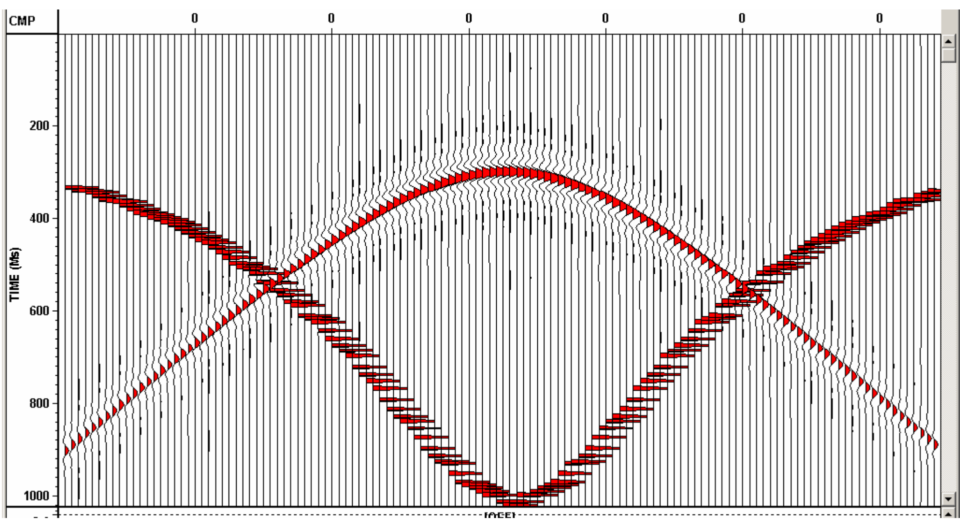


FIG. 14. A single diffraction used for modelling is displayed along with spikes on each trace that illustrate the peak amplitude.

Figure 17 contains the reflection from a reflector that is much larger than the size of the Fresnel zone. The amplitude display indicates that a stable amplitude has been reached at a considerable distance from the edge of the reflector, possible two fresnel radii.

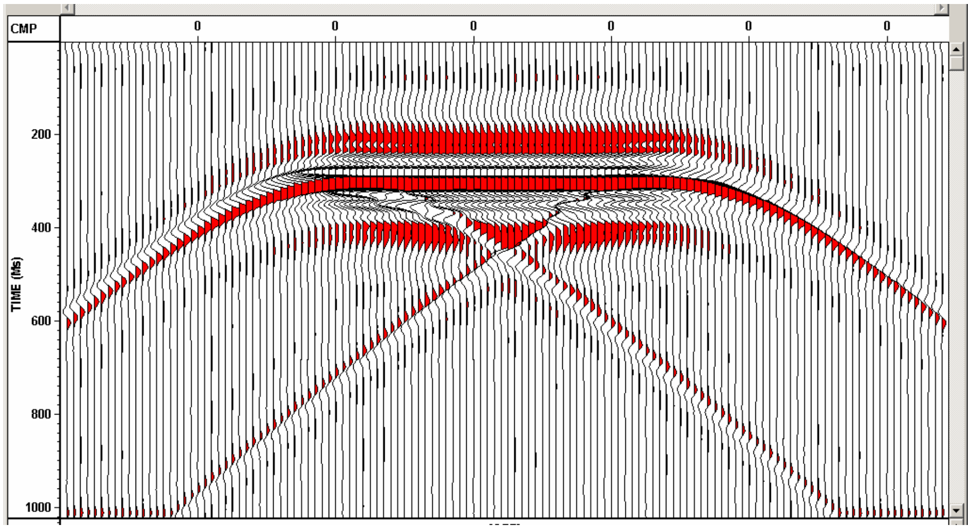


FIG. 15. A reflection from a reflector that is larger than the size of the Fresnel zone, displayed at high amplitude to identify effect of the wavelet.

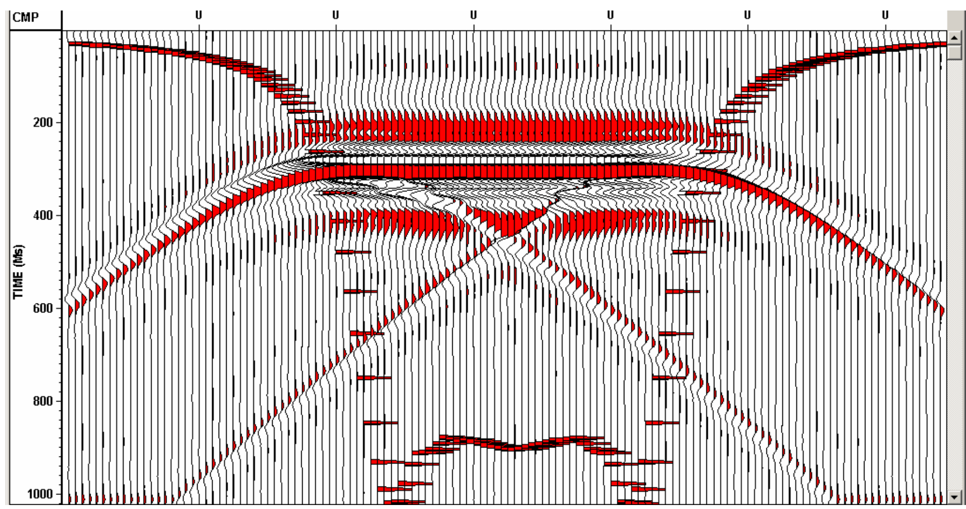


FIG. 16. The reflection of Figure 15 that now contains the amplitude information. The edge effect is still visible at all locations on the reflection.

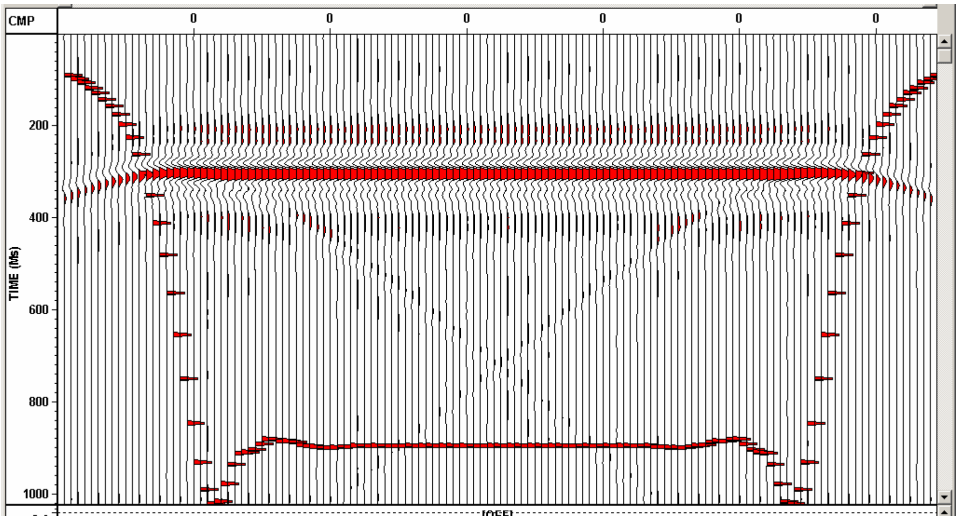


FIG. 17. A reflection from a reflector that is much larger than the size of the Fresnel zone.

CONCLUSIONS

Analytical results of modelling using Berryhill's (1977) method and diffraction modelling were presented to define the size of the edge effect on reflections from the edge truncated reflectors. The size of the Fresnel zone was a good indicator of the size of the edge effect. This size is determined by wavelet length, depth, velocity, and the bandwidth of the signal. The analysis also confirmed the size of a reflector is difficult to determine when its size is close to, or smaller than, the size of the Fresnel zone.

AVO analysis, before migration, can only be performed accurately when the size of a reflector is much greater than the size of the Fresnel zone. Care must be taken to ensure that the AVO analysis location is more than a Fresnel radius from the edge of a reflector.

When a reflector is close to or smaller than the size of the Fresnel zone, AVO analysis can only be performed with a prestack migration.

Only zero offset was considered in this paper. We know that the size of the Fresnel zone increases with offset. Therefore the result in this paper may be quite optimistic, again emphasizing the need for prestack migration.

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