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Short Note

Fresnel zones for broadband data

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INTRODUCTION

For monochromatic waves, the term "Fresnel zone" is well-defined even though different authors use different terminology. Most authors use the definition originating from optics. There, the first Fresnel zone is defined as the area of a circular hole in a screen between a light source and an observation point that produces maximum light intensity in the observation point (Figure 1). If the radius of the hole is enlarged, minima and maxima in light intensity alternate. The first maximum is reached if the raypath difference between the direct ray and the ray traveling via the edge of the hole equals half a wavelength. The extension of the definition to energy reflected from a circular disk is straightforward (if we restrict ourselves to ray theory and neglect the angle dependency of the reflection coefficient) and is illustrated in Figure 2 (see also Sheriff, 1991).

The first Fresnel zone is often used as an indicator of the region that contributes energy (constructively) to the total reflection energy, whereas energy returning from areas outside this region interferes destructively. Berkhout (1984) defines the Fresnel zone differently. Rather than using the area that leads to maximum energy, he defines the first Fresnel zone as the area that returns exactly the desired reflection intensity (but the incorrect wavelet as we will see).

Knapp (1991) proposed a generalization of the definition of the Fresnel zone to broadband signals. We show in this note that his generalization falls short, because in the limit of a very narrow amplitude spectrum, his Fresnel zone is not equal to the Fresnel zone of the corresponding monochromatic signal. We propose an alternative generalization of the definition of the first Fresnel zone to broadband signals and illustrate that the Fresnel zone depends mainly on the dominant frequency of a wavelet. The restriction of the reflector area to the Fresnel zone, however, does not produce the desired wavelet for broadband signals.

Knapp's Fresnel zone for broadband signals is in fact the area on the reflector that guarantees the correct wavelet and amplitude of the reflected signal. The size of this area depends on the length of the wavelet. Because "Fresnel zone" is not a fitting term for this area, we propose to use the terminology "zone of influence."

FRESNEL ZONES FOR BROADBAND SIGNALS

Consider a circular horizontal reflector with radius r in a medium with constant velocity c. The contribution to the reflected signal of all secondary sources within a certain area can be computed using the Kirchhoff integral over the area. This integral can be solved analytically [Trorey's formula, Knapp, 1991, equation (3)]:

$$R(t) = \frac{1}{T_0} f(t - T_0) - \frac{h}{T\xi} f(t - T), \tag{1}$$

in which $R(t)$ is the reflected signal, $f(t)$ is the source wavelet (including reflection coefficient), h is the depth of the reflector, T_0 is the two-way normal-incidence time to the reflector, ξ is the distance to the edge of the reflector, and T is the two-way traveltime to the edge of the reflector. The first term is the desired reflection, the source wavelet retarded by the time T_0 and multiplied with the geometrical spreading $1/T_0$. The second term is the polarity reversed source wavelet with retardation T (corresponding with a truncation effect caused by the finite integration area).

For a source wavelet of duration Δt, the desired reflection and the truncation effect separate for $T \geq T_0 + \Delta t$, whereas there is interference for smaller values of T. (Because physical one-sided wavelets are usually of infinite length, the duration of such a wavelet has to be suitably defined in practice, e.g., the first part of the wavelet containing most of the energy.) For a reflector with infinite radius the truncation term vanishes, then $R(t)$ is exactly equal to the desired reflection.

Using equation (1), the energy of the reflected signal as a function of the reflector radius can be computed. Figure 3 shows the energy function for three different source wavelets with $h = 1000$ m and $c = 2000$ m/s. For a monochromatic

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signal (Figure 3a) the energy is oscillating. The first maximum of the curve defines the boundary of the first Fresnel zone, the other extrema correspond with the boundaries of the higher order Fresnel zones. The energy function is similar to the function displayed in Figure 2 in Knapp (1991).

For a signal with a relatively narrow spectrum (Figure 3b), the energy function oscillates as well. The oscillations, however, disappear at the radius corresponding to $T = T_0 + \Delta t$, beyond which the reflection and the truncation effect are separated. The energy function of the broadband signal in Figure 3c builds up to a maximum as is also similar for the other signals, but it quickly stabilizes. Thereafter, the energy decreases monotonically because of the vanishing amplitude factor of the truncation term in equation (1).

Comparison of the various energy functions in Figure 3 suggests a straightforward generalization of the definition of first Fresnel zones to broadband signals: *The boundary of the (first) Fresnel zone corresponds to the position of maximum energy build-up.*

Since higher-order Fresnel zones cannot, in general, be identified for broadband signals, we may just as well drop the adjective "first" from the definition. Note that the definition given in Berkhout (1984) can be generalized in a similar way: *Berkhout's (first) Fresnel zone for broadband signals would correspond to the smallest zone for which the energy of the reflected wavelet equals the energy of the input wavelet.*

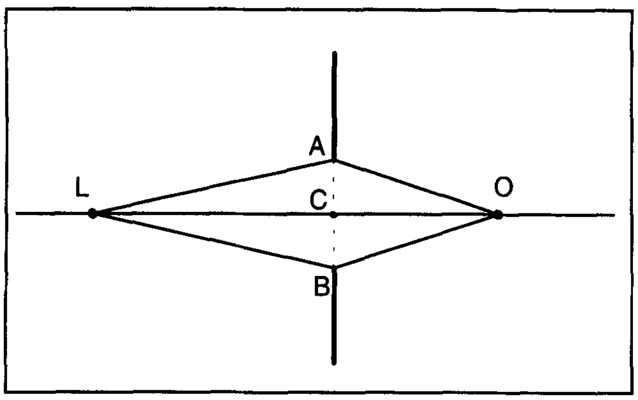

FIG. 1. Definition of the first Fresnel zone in optics. L is a monochromatic light source with wavelength λ, O is the observation point, and AB is a circular hole in a screen. AC is the radius of the first Fresnel zone if LAO = LCO + $\frac{1}{2}\lambda$.

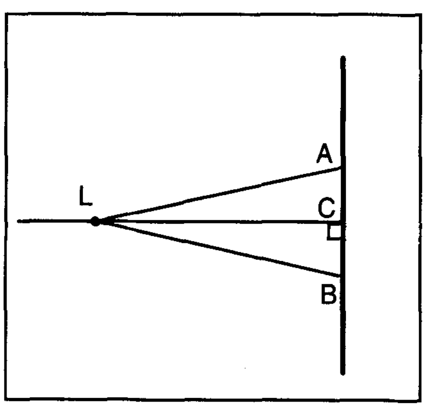

FIG. 2. Extension of the definition of the radius of the first Fresnel zone for a reflected monochromatic wave with coincident light source and observation point. AC is the radius of first Fresnel zone if LA = LC + $\frac{1}{4}\lambda$.

The radius of the Fresnel zone is determined mainly by the dominant frequency of the wavelet. As the dominant frequency is the same for all three input wavelets, the initial parts of the energy functions are virtually identical. The higher the dominant frequency, the smaller the radius of the Fresnel zone. The radius also depends on the bandwidth of the signal. Though hardly visible, the maximum in Figure 3c is not only smaller than for the other two signals, it also occurs for a somewhat smaller radius.

THE ZONE OF INFLUENCE

The length Δt of the wavelet determines the radius where the truncation effect [second term in equation (1)] is fully separated from the reflected wavelet [first term in equation (1)]. Obviously, this radius is different from the Fresnel zone radius and should be given a different name, for which we propose the term "radius of influence" and for the corresponding area on the reflector we propose the term "zone of influence."

The zone of influence is the area on the reflector for which the difference between the reflection traveltimes and the diffraction traveltimes is less than the length Δt of the wavelet.

For monochromatic waves this zone would be infinite. A comparison with the definition of the Fresnel zone for broadband signals in Knapp (1991) shows that Knapp's definition in fact describes the zone of influence. This is indeed the zone that should be used in true-amplitude modeling to determine the minimal range over which to extend the secondary sources. Beyond this range summation tails can be tapered out.

Restricting the reflector radius to a radius smaller than the radius of influence would result in a change of the reflected wavelet with respect to the input wavelet. This change is caused by the interference between the desired reflected wavelet and the truncation effect. Figures 4 and 5 illustrate these points for a narrow-band wavelet (Figure 4a) and a broadband wavelet (Figure 5a), respectively. Figures 4b and 5b show the wavelets that have the same energy as the input wavelets. These wavelets are produced by reflection from the generalized Fresnel zone corresponding to Berkhout's definition of Fresnel zone. Figures 4c and 5c show the wavelets with maximum reflected energy. These wavelets are produced by reflection from the generalized Fresnel zone corresponding to the conventional definition of Fresnel zone. Figures 4d and 5d show that the input wavelet is reproduced if the reflector area is equal to or larger than the zone of influence. Only then the truncation effect, being separated from the desired reflected wavelet, can be removed by tapering.

Note that our definition of the zone of influence can be further generalized to reflections from curved interfaces in complex geology and to non-normal incidence. To this end, "radius" in the definition above is understood to be an azimuth-dependent quantity defined by the distance between the specular point and the point on the reflector where the traveltime difference between the two points equals $\pm\Delta t$

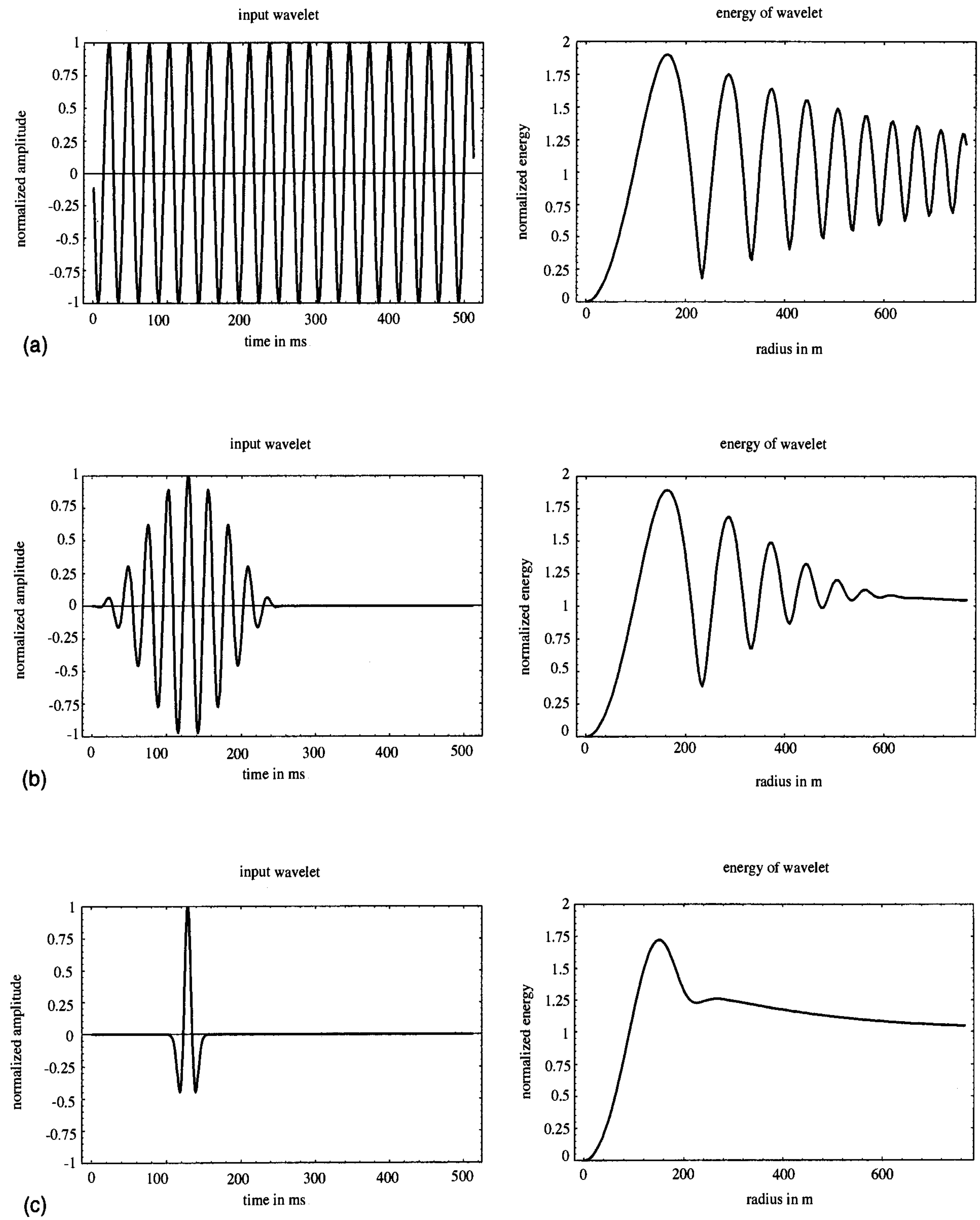

FIG. 3. Illustration of Fresnel zones for different wavelets. The input wavelets are shown on the left, all with central frequency of 37.1 Hz; the energy as a function of the radius of a circular reflector is on the right. The reflector depth is 1000 m; the velocity is 2000 m/s. The Fresnel zone is, in all cases, defined by the maximum of the energy function. (a) Monochromatic wavelet, (b) narrowband wavelet, (c) broadband Ricker wavelet.

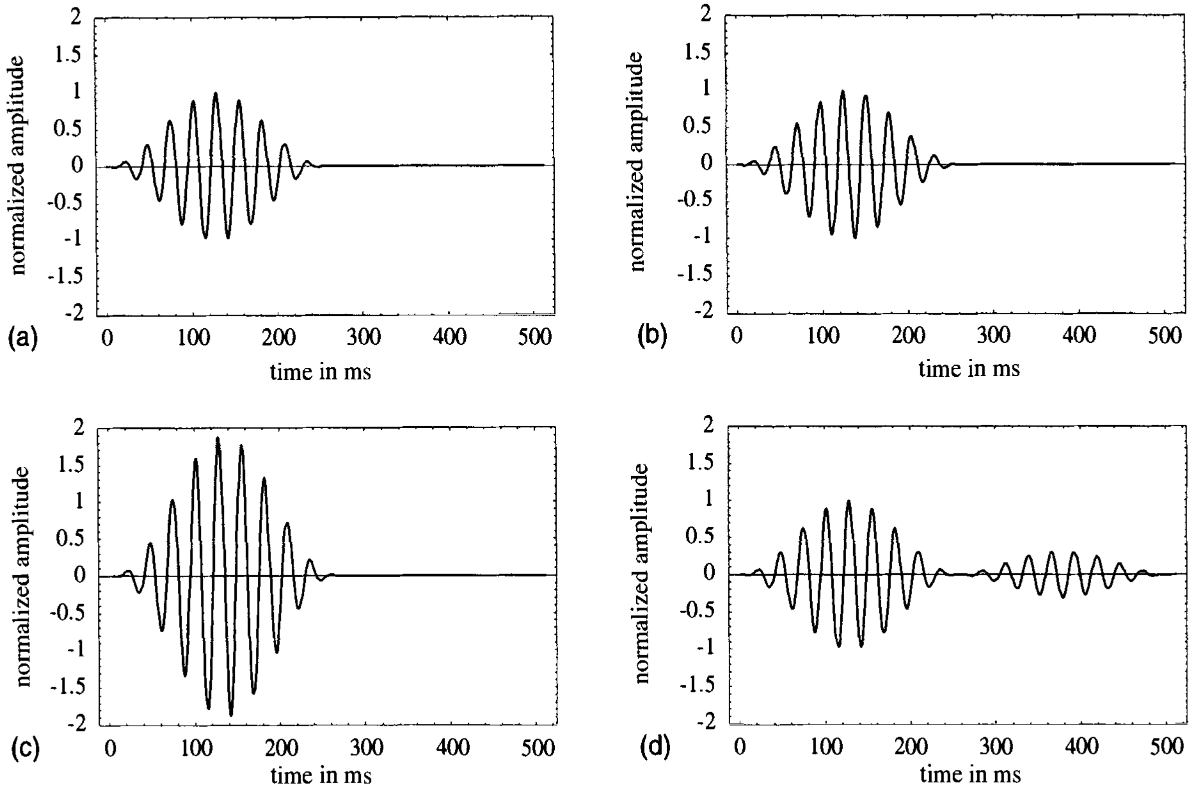

FIG. 4. The reflected wavelet as a function of the radius of a circular reflector. (a) Input wavelet; (b) reflected wavelet for smallest radius for which normalized energy equals 1, i.e., radius corresponding to our generalization of Berkhout's definition of Fresnel zone; (c) reflected wavelet with maximum normalized energy, i.e., radius corresponding to generalized Fresnel zone; (d) reflected wavelet for radius that is large enough to allow separation of desired reflected wavelet and truncation effect, i.e., radius corresponding to zone of influence.

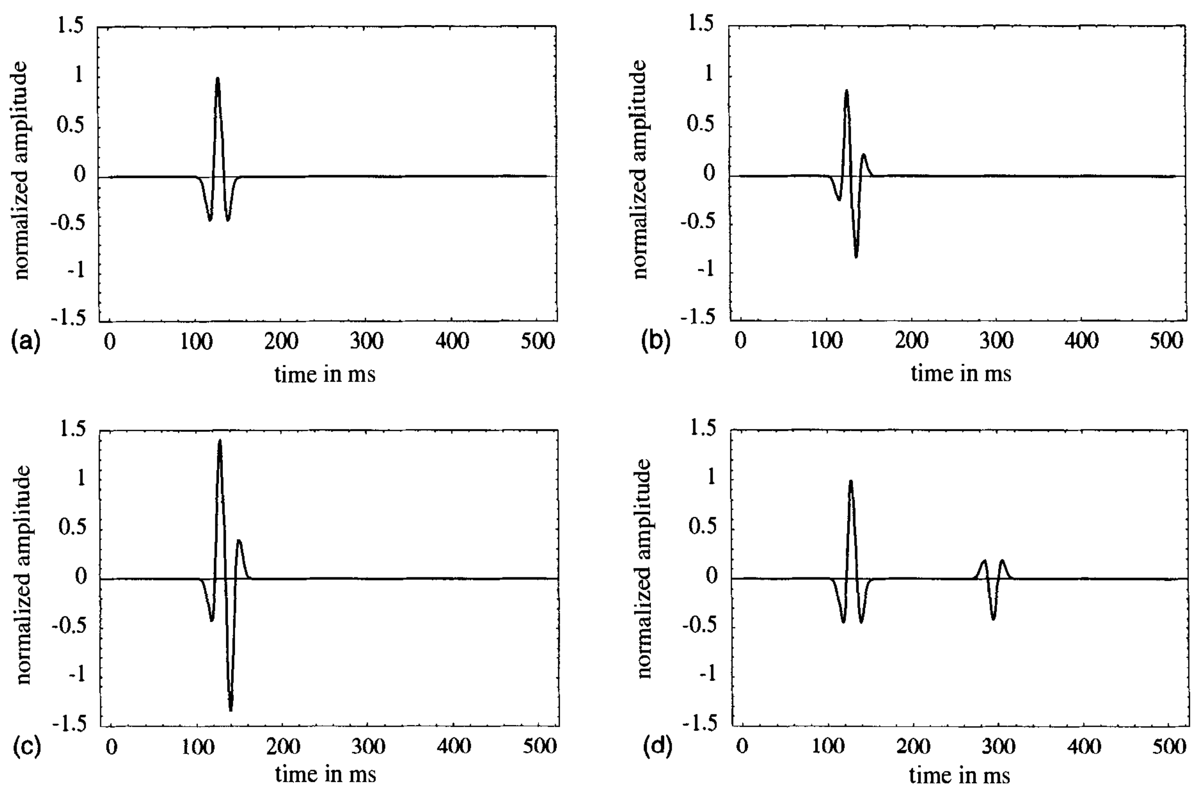

FIG. 5. Same as Figure 4, but now for a broadband wavelet. Note that only in (d) is the correct wavelet shape reproduced.

(minus sign for locations where the traveltime reaches a maximum close to the specular point).

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