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Imaging primaries and multiples simultaneously with depth-focusing

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ABSTRACT

Seismic imaging amplitudes are extracted with the imaging conditions $t = 0$ and $h = 0$, where $t = 0$ means that the take-off time of the upward-coming wave is zero, and $h = 0$, with h the half-offset between the source and receiver position, means that the downward-going and upward-coming waves meet together during the wavefield extrapolation. However, $h = 0$ makes no sense for multiples imaging. This imaging condition is suitable for imaging the primary, where the source position must be known. I introduce an imaging condition for imaging primaries and multiples simultaneously. The imaging condition, in essence, states that the take-off time of the upcoming wave equals zero, and that the radius of curvature of the wavefront of the upcoming scattered wavefield equals zero. It is known that the primary and multiple scattered waves will be focused during the wavefield depth extrapolation, but the primary and multiple scattered waves at the same depth focus at different times; this is because the traveltimes from the source to the scattering point are different for the primaries and multiples, even for the same scattering point. The focused scattered wave can be picked out, and the image is formed at the focusing point. The advantages of the method are several: the primary and multiples can be imaged simultaneously, only the up-coming wave must be downward extrapolated, all the scattered wavefields in the different shot gathers can be added together and simultaneously extrapolated, and the source position needs not be known. Its disadvantage is that the imaging condition is much more difficult to use.

INTRODUCTION

Usually, multiples in seismic data have been considered as noise for the imaging of the primaries (Berkhout and Verschuur, 1997). This is because it is difficult to put the multiples onto their scattering points, since the commonly used imaging conditions can not correctly and simultaneously pick up both the focused primaries and multiples. Schuster et al. (2003) proposed that if the source below the surface is unknown, the autocorrelation of each trace can be used to determine a pseudo source on the surface, since the autocorrelation of the direct wave is $t = 0$ time delay and the direct wave is thus eliminated in the autocorrelogram. The autocorrelogram can be thought to be acquired with the pseudo shot-receiver pair at the surface. Therefore, conventional prestack depth migration can focus and image ghost wave, or the

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first-order multiple. However, the disadvantages of the method are that the autocorrelogram does not satisfy the wave equation, and the traveltime of the direct wave can not be correctly estimated and cancelled, which makes the travel time calculation in the integral migration not match the travel time in the autocorrelogram and the imaging noises occur. The crosstalk in the autocorrelogram also causes the imaging noise. On the other hand, the ghost wave is the first-order multiple and the imaging of higher-order multiples is ignored.

The imaging condition proposed by Claerbout (1971) should be modified if primaries and multiples are simultaneously imaged, whether the source position is known or unknown. The imaging condition I propose states that the radius of curvature of the wavefront equals zero. This is called the depth-focusing imaging condition. MacKay and Abma (1993) use depth focusing to carry out velocity analysis. If the migration velocity is larger than the medium velocity, then the focusing depth is less than the reflection depth, and the imaging depth is larger than the reflection depth; on the other hand, if the migration velocity is less than the medium velocity, then the focusing depth is greater than the reflection depth, and the imaging depth is less than the reflection depth. The real reflection depth lies at the mid-point between the focusing depth and the imaging depth. In that paper, the authors proposed a method for estimating the radius of the curvature of the wavefront. However the formula is suitable only for imaging the primaries. For a given scattering point, the primary and multiple scattering from it are simultaneously focused at the same depth in the model space and at different times in the data space with the downward wavefield continuation. The "focusing" means that the received scattered wavefield is collapsed into the scattering point, and the radius of curvature of the wavefront diminishes to zero. With the depth-focusing imaging condition, the focused imaging values of the primary and multiples can be simultaneously picked up from the depth-extrapolated wavefield, which is expressed in the time domain. The following are some advantages of depth-focusing imaging. The primaries and multiples (including the higher-order multiples) can be simultaneously imaged; the source position can be known (for the primaries) or unknown (for the multiples); all of the scattered wavefield can be added together, and computation efficiency can be improved. The disadvantage is that the depth-focusing imaging condition is difficult to use, especially for data with a lot of noise.

PRINCIPLES OF FOCUSING

Figure 1 geometrically shows the depth-focusing process of the primary scattered wavefield, and Figure 2 shows the same process for the multiple scattered wavefield. Comparing the two figures, it is clearly seen that the focusing process is the same for a scattering point, whether the scattered wavefield from it is primary or multiple scattering. The imaging condition of prestack migration is that the arrival time of the downgoing wave equals the take-off time of the upcoming wave (Claerbout, 1971). However, conventionally, the downgoing wave means the primary downgoing wave, not the multiple downgoing wave. It is difficult to determine the traveltime of the multiple downgoing wave. Therefore, with this imaging condition, it is difficult to image the primaries and the multiples simultaneously. The conventional imaging condition implicitly tell us that the image of a reflector appears at the point, at which the received scattered wavefield is collapsed. At that point, the arrival time of the downgoing wave

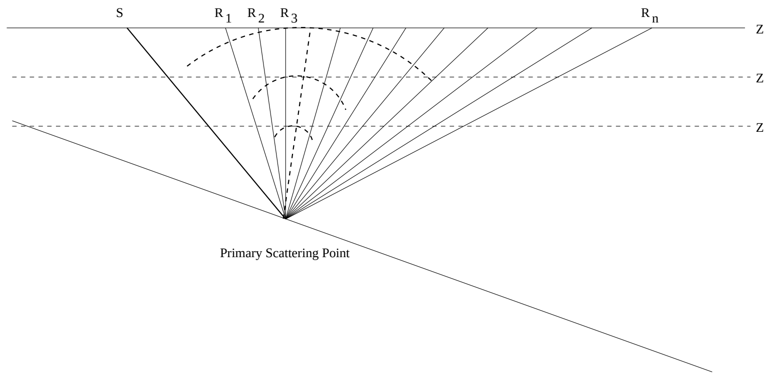

Figure 1: The depth focusing of the primary scattering wavefield with the extrapolation. The radius of curvature of the wavefront diminishes to zero with the downward wavefield continuation. huazhong2-Scattering_primary [CR]

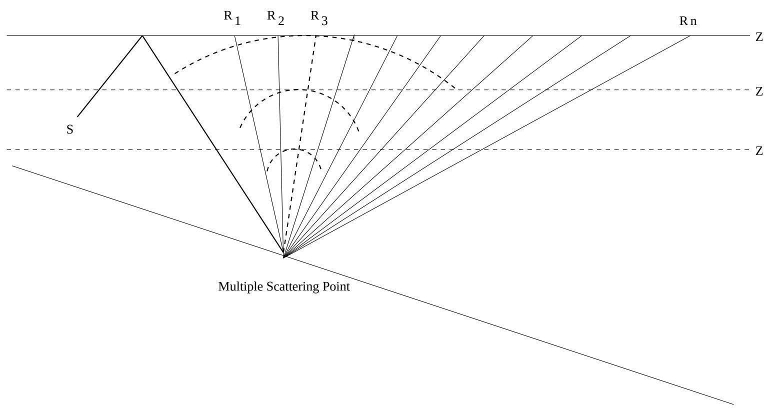

Figure 2: The depth focusing of the multiple scattering wavefield with the extrapolation. The source position can be unknown. The radius of curvature of the wavefront diminishes into zero with the downward wavefield continuation. The higher-order multiples can be focused also. huazhong2-Scattering_multiples [CR]

equals the take-off time of the upcoming wave, and the radius of curvature of the scattered wavefield diminishes to zero. The radius of curvature of the scattered wavefield diminishes to zero means that the scattered wavefield is focused to the scattering point. Unlike imaging for the primaries, for imaging of multiples, the concept of offset makes no sense. For multiples imaging, the offset should be calculated with the "pseudo" source and receiver position. However, it is not easy to determine the "pseudo" source position for the higher-order multiples. In fact, the statement that the arrival time of the downgoing wave equals the take-off time of the upcoming wave is equivalent to saying that the radius of curvature of the scattering wavefield diminishes to zero. However, the latter is much more prevalent than the former. The latter can be used to image the primaries and the multiples, whether the source position is known or unknown, because the only criterion is whether the scattering wavefield is focused or not. The latter can be called the depth-focusing imaging condition. The former is a model-driven process; the latter is a hybrid-driven process. Wavefield extrapolation is model-driven, and picking the focused amplitude is data-driven.

IMPLEMENTATION OF DEPTH-FOCUSING

Estimating whether the scattering wavefield is focused or not is difficult for simultaneously imaging primaries and multiples with depth-focusing. The wavefield extrapolation is carried out in the depth domain, and picking the image amplitude must be implemented in the time domain, since the traveltime from the source to the scattering point is not necessarily known.

Assuming that the macro velocity model is reliable, the horizontal positions of the focused scattering points are correct. The wavefield extrapolation depth determines the focused depth, which is also correct under the assumption. The obvious method is to use the amplitude of the focused scattering wavefield. When a scattered wavefield is focused, the amplitude at the focused point is maximized. During the process of wavefield extrapolation, the amplitude of the wavefield at every point fluctuates. Therefore, the amplitude itself can not be used as an indication. Other attributes should be used, such as the envelope of the amplitudes, the derivative of the envelope, and so on. Hence, several extrapolated wavefields should be saved, including the current extrapolated layer and its adjacent layers. This helps to avoid picking the wrong focused amplitude.

Another method is to estimate the radius of curvature of the wavefront of the scattering wave. MacKay and Abma (1993) present a method that, in the CMP geometry, uses the following formula:

$$R \approx \frac{\left(X^2 - \triangle t^2 V_r^2\right)}{2\triangle t V_r}, \tag{1}$$

where X is the offset, V_r is the medium velocity, and $\triangle t$ is the time difference between the two-way vertical traveltime and the observed traveltime. However, this formula is not suitable here, because the time difference is unknown. For depth-focusing imaging, the source position is not a concern, and the traveltime between the source and the scattering point is not explicitly used. I propose the following method to estimate the radius of curvature of the scattered wavefield. Assuming that the macro velocity is correct, and with the help of ray-tracing, the radius of curvature of the scattered wavefield can be estimated with the following formula:

$$R = V_r t_{scatter}, \tag{2}$$

where $t_{scatter}$ is the traveltime from the scatterer to the receivers, V_r is the medium velocity, and $\triangle t = t - t_s = t_{scatter}$, where t is the observed two-way traveltime and t_s is the traveltime from the source to the scatter point. t_s may include the traveltime of the multiples. According to equation 2, the radius of curvature of the scattered wavefield can be estimated with the extrapolated wavefield. Some ideas in Jager et al. (2001) suggest how to estimate the radius of curvature of the scattered wavefield.

DISCUSSION AND CONCLUSION

I propose a new imaging condition, with which the wavefield extrapolation is carried out in the depth domain, and the imaging amplitude is extracted from the focused scattered wavefield in the time domain, if the radius of curvature of the wavefront diminishes to zero. I call this imaging condition the depth-focusing imaging condition. I assert that the statement that the arrival time of the downgoing wave equals the take-off time of the upcoming wave is equivalent to saying that the radius of the curvature of the scattering wavefield diminishes to zero. With the imaging condition, the primaries and the multiples can be simultaneously imaged. The source position can be known or unknown; therefore the passive data can be imaged with it. Some shot gathers can be added together according to the receiver positions, and then the new data set is imaged with the above method, thus improving the calculation efficiency. The depth-focusing imaging condition can be used for imaging multicomponent seismic data. However, since the focusing of the scattering wave is detected in the time domain, the data needs to have high S/N ratio. It will be best suited for processing marine data.

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