3D Fast illumination analysis for arbitrary acquisition system using plane waves

Jian Mao, James Sheng, Bin Wang and Connie VanSchuyver, TGS*

Summary

We develop a new efficient scheme of illumination analysis for arbitrary acquisition system using plane waves. With this scheme, we can calculate the total illumination efficiently which considers the distribution of source and receivers. Therefore, it can be a useful tool to study the influence of the model (e.g. salt body) and the acquisition system (e.g. shot distribution and aperture size). This can be used for acquisition design and model building. In the past, to calculate illumination for a given source and receiver distribution, we have used Green's function for every subsurface location. For efficiency, we can reduce the computational cost by calculating Green's function sparsely. Consequently, the shallow part of the illumination map may include footprints from this approach. Here, we proposed a new method using plane waves instead of calculating the single point Green's function for the receiver side. Our simulation includes a number of plane waves with different takeoff angles from all the receiver locations for each shot. This routine, coupled with source-side illumination, properly calculates the illumination for a given acquisition system. Furthermore, this method out performs previous techniques for all types of illumination analysis, including large scale 3D input. Our demonstration includes a 2D Kepler salt model dataset to confirm the validity of our method, and then progresses to a 3D Freedom/Patriot model with an orthogonal shooting application.

Introduction

In the Gulf of Mexico, huge salt bodies always exist in the acquisition area, which results in a severe illumination problem especially in the subsalt area. Seismic illumination studies promote our understanding of how the subsurface structure and specific acquisition design influence imaging targets. This illumination analysis provides an estimation of the energy distribution in the subsurface, which helps us improve acquisition design and increases understanding of the migrated image. Ray-based illumination methods (Bear et al., 2000, NORSAR software) are very popular and efficient. However, they are not accurate enough to handle very complex structure, such as a salt dome where sharp velocity contrasts exist. To solve this problem, wave-equation based illumination analysis methods are proposed (Rickett, 2003; Jin and Xu, 2010). These have added cost, but provide reliable illumination for complex structures.

Illumination analysis can also be done in the angle domain, which provide us with a better understanding of the influence of dipping structures in the subsurface (Wu and Chen, 2006; Xie et al., 2006; Cao and Wu, 2009). However, angle decomposition is very expensive, especially in the 3D case. Our implementation required additional effort to make this calculation efficient for high performance illumination analysis in the 3D case (Mao and Wu, 2007; Mao et al., 2010). In addition, we have included the flexibility to operate on a target-oriented basis. (Mao et al., 2013).

It's relatively easy to calculate the source side total illumination, which is a summation of the energy of all the sources. However, because the acquisition aperture is also an important factor for the illumination analysis, we have to take the receiver distribution into account for a specific acquisition system. High-accuracy calculations for our source, receiver distribution are accomplished by applying Green's function for each source and receiver location and summing all coupled energy for each source, receiver pair. For a 3D case, this approach is not feasible because there are too many Green's functions to calculate. In a real application, we usually calculate a subset of Green's functions for a survey, which is more efficient, but will include footprint artifacts.

In this study, we develop an efficient scheme of illumination analysis for given acquisition survey. Here, we use the wave-equation based migration in the frequency domain. Instead of calculating of single point Green's function for the receiver side, we simulate a number of plane waves with different takeoff angle from all the locations of receivers in each shot. Together with the source-side illumination, we can calculate the illumination for the given acquisition system. This scheme provides a useful tool for acquisition design and analyzing the image amplitudes. We calculated several numerical examples including a real application of a 3D data.

Illumination analysis for given acquisition system

For a given acquisition geometry, we use a wave-equation based propagator to get the frequency-space Green's function $G(\boldsymbol{x}, z, S, \omega)$ from the source S to the subsurface point $(\boldsymbol{x}, z)$. Then we can get the total illumination by the summation of the energy from all the sources:

$$D_{total}(\boldsymbol{x}, z, \omega) = \sum_s |G(\boldsymbol{x}, z, S, \omega)|^2. \qquad (1)$$

To produce the source, receiver illumination for a specific acquisition survey, we have to calculate all the Green's functions from all the receivers. Similarly for the source

DOI http://dx.doi.org/10.1190/segam2014-1300.1

side, the frequency-space Green's function $G(\boldsymbol{x}, z, r, \omega)$ from the subsurface point $(\boldsymbol{x}, z)$ to receiver r can be also calculated by wavefield extrapolation. We use the reciprocity principle for calculation of the receivers' Green's function, which means we calculate the Green's function from the receiver to the subsurface point and use it for the illumination analysis. However, this approach is not feasible in 3D case, because there are too many Green's functions to calculate due to dense receiver sampling. For example, if we are processing a 20 km*20 km*10 km area and use 20 m grid size for all the three dimensions, we would need to calculate 1,000,000 Green's functions, requiring 2000 TB of disk storage. In a real application, we usually calculate subsampled Green's functions for the whole survey. Likewise additional compromises between the disk I/O and repeated computation must also be made for real data application. However, these compromises will affect the accuracy and may have some footprint artifacts.

In order to evaluate the aperture and propagation effects of a given acquisition geometry for energy distribution more efficiently, we propose a plane-wave method. For a given source location and receiver distribution, we simulate a number of plane waves $P(\boldsymbol{x}, z, \boldsymbol{k}_r, \omega)$ from all the receivers' location to the subsurface, where is the wavenumber of the plane wave representing the direction. Then the total illumination can be calculated as:

$$A(\boldsymbol{x}, z, \omega) = \sum_s |G(\boldsymbol{x}, z, s, \omega)|^2 \sum_{\boldsymbol{k}_r} |P(\boldsymbol{x}, z, \boldsymbol{k}_r, \omega)|^2. \quad (2)$$

which is a summation of all the energy from the coupled source and plane waves. In this way, we can calculate the illumination as the prestack one-way migration or reverse-time migration.

The scheme of illumination analysis using plane wave

First, let's review the old scheme for illumination calculation. Initially, the velocity model and acquisition information (shot by shot) is input. For each shot, we loop over the possible shot and receiver locations to calculate Green's functions. After the computation of all Green's functions is complete, multiplication and summation are accomplished to produce illumination for this shot. When the illumination of all the shots is calculated, intermediate results are stacked, resulting in total illumination. This procedure is similar to prestack migration. The main difference in our new scheme is that the loop for the receivers' location is replaced by a loop for the wavenumber of plane waves. Figure 1 shows the flowchart of the new scheme. In our real calculation, we usually choose 15 wavenumbers in both X- and Y- direction, which means we calculate plane waves with 225 different take-off angles. The old scheme required calculation of thousands of Green's functions, which is not efficient. Therfore, the new methodology will be a huge improvement over the previous. For example, if the aperture is 8 km by 8 km with 20 m grid spacing for both X- and Y- direction, we have to calculate 400*400 Green's functions ideally. Even if we cut this to 1/100 of the total number, we still need to caculate 1600 Green's functions. Since the cost of computing one Green's fucntion is the same as that of a plane wave. Our plane wave method can be almost 8 times faster than the old scheme in this case. We can avoid repetitive computation by saving the Green's functions to disk. However, it requires a large disk space for storage and high I/O cost. While the new scheme does not require storage for calculations the illumination computation is similar to prestack migration. Since the new scheme is very efficient, it allows illumination analysis for large surveys areas with minimal turn around time, which is useful during acquisition design.

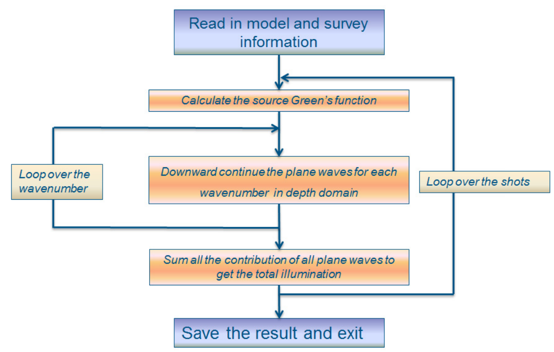

Figure 1 Flowchart of the illumination scheme

Numerical examples

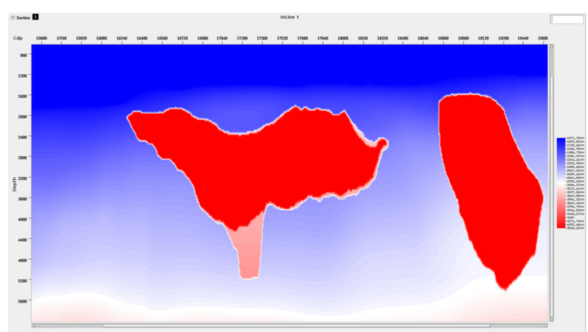

Figure 2: 2D velocity section of a field example

We first use a 2D example to demonstrate the validity for the new method. This 2D model is extracted from the Kepler 3D WAZ acquisition in North America. Model range for this dataset is approximately 33 km in inline direction and 6 km in depth. A simulated survey with 92 shots was located at the surface. Figure 2 shows the

DOI http://dx.doi.org/10.1190/segam2014-1300.1

velocity model, while Figure 3 demonstrates the total source-receiver illumination which is calculated by the old time-consuming scheme. Our plane wave method is then applied to achieve illumination for the whole acquisition survey. Figure 4 illustrates the illumination distribution produced from the new method, which has the similar quality compared to the old scheme but it's 4 times faster in this case. Illumination in the subsalt area is very weak as expected, which means the image quality will be influenced dramatically by the large salt body.

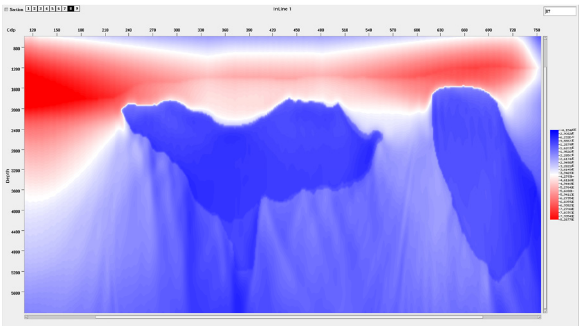

Figure 3: Source-Receiver illumination map by old scheme

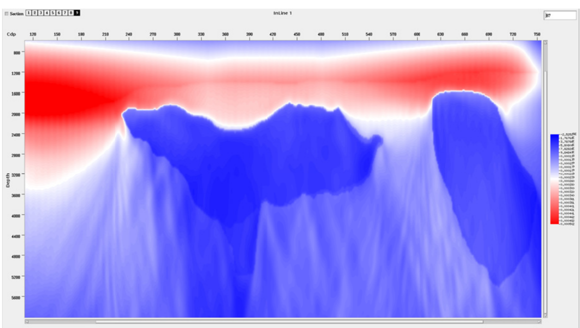

Figure 4: Source-Receiver illumination map by new scheme

Finally, we examine a real 3D dataset in North America. For this examination we use the Freedom/Patriot 3D WAZ dataset. Freedom 3D WAZ data is acquired by TGS several years ago. For better coverage, we obtained an additional orthogonal acquisition in the same area named Patriot 3D WAZ acquisition. Freedom acquisition is inline sailing direction and Patriot acquisition is crossline sailing direction. Since the sailing directions of these two acquisition surveys are perpendicular to each other, we describe it as orthogonal shooting. This survey area includes several enormous salt bodies in the subsurface, which caused a severe illumination problem, so the orthogonal shooting acquisition delivers superb coverage in the subsurface. We produced an illumination-energy distribution for the orthogonal surveys.

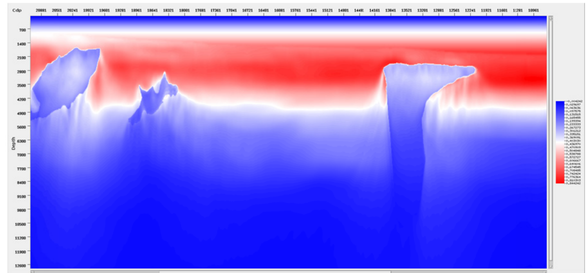

Figure 5: Inline illumination section for Freedom WAZ acquisition

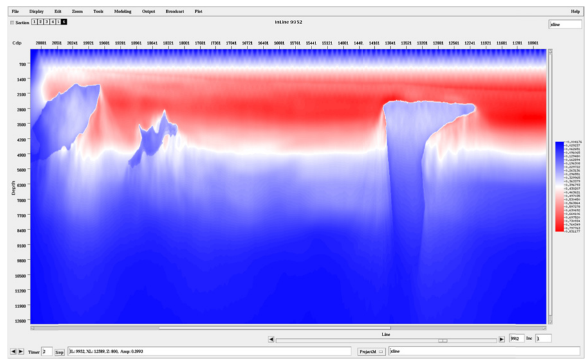

Figure 6: Inline illumination section for Patriot WAZ acquisition

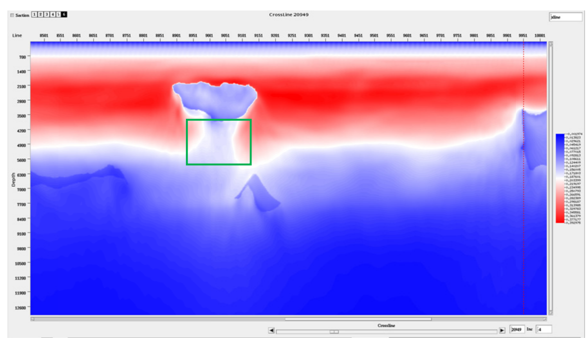

Figure 7: Crossline illumination section for Freedom WAZ acquisition

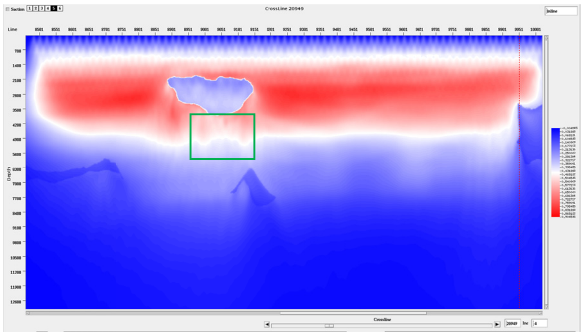

Figure 8: Crossline illumination section for Patriot WAZ acquisition

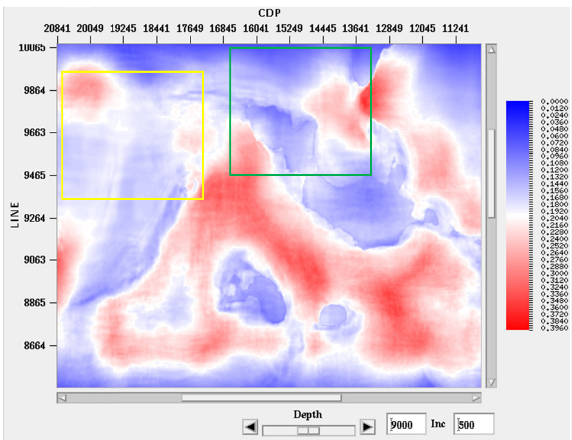

Figure 9: Depth slice of the illumination for Freedom WAZ acquisition

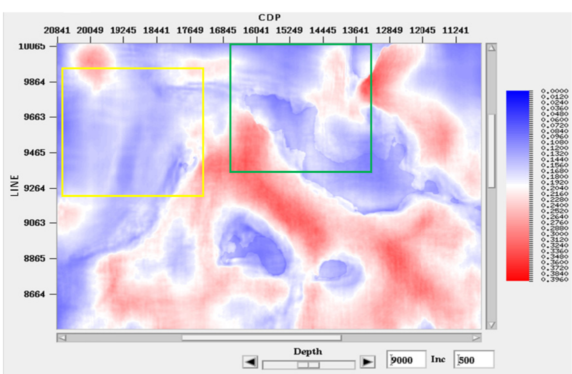

Figure 10: Illumination depth slice for Patriot WAZ acquisition

Figure 5 and Figure 6 are the inline section of the illumination for the Freedom WAZ acquisition survey and Patriot WAZ acquisition survey respectively. Figure 7 and Figure 8 show a crossline section of the illumination for the Freedom WAZ and Patriot WAZ acquisition survey. Derived from the illumination map, we can see the energy distribution is notably different, especially for the subsalt area. In Figure 8, we display the illumination for the subsalt region, notice the left part (green box) is stronger than that in Figure 7. Figure 9 and Figure 10 provide the depth slice of the illumination for these two surveys. Major differences for these two results are indicated by the boxed areas. As a result, the Patriot WAZ acquisition and Freedom WAZ acquisition are perfect complements of each other, which highlights the advantage of the orthogonal acquisition.

Our 2D and 3D data examples demonstrate that this illumination-analysis scheme is successful. Application for large-scale illumination analysis is valid because of its high efficiency.

Conclusions

We developed an efficient method to calculate illumination analysis for a given subsurface model and acquisition survey. Using the plane wave method, source-receiver coupled illumination maps are generated more efficient than the conventional scheme. Furthermore, our examples demonstrated the validity of our method using a 2D salt model and 3D field example. Our orthogonal shooting case extended our understanding as it relates to survey design and illumination.

Acknowledgement

We thank TGS for the permission to publish this work. We also thank Zhiming Li, Sang Suh, Jean Ji, Yang He, and Xiang Xiao for helpful discussion.

DOI http://dx.doi.org/10.1190/segam2014-1300.1

http://dx.doi.org/10.1190/segam2014-1300.1

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2014 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Bear, G., C.-P. Lu, R. Lu, D. Willen, and I. Watson, 2000, The construction of subsurface illumination and amplitude maps via ray tracing: The Leading Edge, **19**, 726–728, http://dx.doi.org/10.1190/1.1438700.

Cao, J., and R.-S. Wu, 2009, Full-wave directional illumination analysis in the frequency domain: Geophysics, **74**, no. 4, S85–S93, http://dx.doi.org/10.1190/1.3131383.

Jin, S., and S. Xu, 2010, Visibility analysis for target-oriented reverse-time migration and optimizing acquisition parameters: The Leading Edge, **29**, 1372–1377, http://dx.doi.org/10.1190/1.3517309.

Lecomte, I., 2006, Illumination, resolution, and incidence-angle in PSDM: A tutorial: 76th Annual International Meeting, SEG, Expanded Abstracts, 2544–2548.

Mao, J., and R.-S. Wu, 2007, Illumination analysis using local exponential beamlets: 76th Annual International Meeting, SEG, Expanded Abstracts, 2235–2239.

Mao, J., R.-S. Wu, and J.-H. Gao, 2010, Directional illumination analysis using the local exponential frame: Geophysics, **75**, no. 4, S163–S174, http://dx.doi.org/10.1190/1.3454361.

Mao, J., S. Suh, and B. Wang, 2013, Angle-domain illumination analysis along a target horizon: 83rd Annual International Meeting, SEG, Expanded Abstracts, 191–195.

Rickett, J. E., 2003, Illumination-based normalization for wave-equation depth migration: Geophysics, **68**, 1371–1379, http://dx.doi.org/10.1190/1.1598130.

Wu, R.-S., and L. Chen, 2006, Directional illumination analysis using beamlet decomposition and propagation: Geophysics, **71**, no. 4, S147–S159, http://dx.doi.org/10.1190/1.2204963.

Xie, X.-B., S. Jin, and R.-S. Wu, 2006, Wave-equation-based seismic illumination analysis: Geophysics, **71**, no. 5, S169–S177, http://dx.doi.org/10.1190/1.2227619.