Evaluation of 3D seismic survey design parameters through ray-trace modeling and seismic illumination studies: a case study

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Abstract
This paper describes a case study of wavefront construction-based ray-trace modeling to access the 3D seismic exploration parameters that significantly impact achieving the exploration target in seismic data acquisition. The traditional methods assessment is based on the horizontal reflector concept, which does not consider the subsurface's inhomogeneities. This case study provides a methodology by considering the effect of subsurface variations on the estimation of seismic survey parameters. As the first step in this methodology, an elastic earth model is created to propagate theoretical seismic rays from a 3D seismic survey to generate seismic ray properties. Then illumination maps and synthetic seismic sections are generated from these seismic ray attributes to evaluate seismic survey performance in seismic imaging targets. The results proved that the method helps estimate seismic survey efficiencies in seismic target imaging. Therefore, the ray-trace modeling methodology can help obtain the target fold coverage in complex geological settings by designing and verifying the seismic survey parameters.

Keywords 3D Seismic survey design · CMP Fold · Ray-trace attributes · Illumination maps · Wavefront construction · Seismic ray-trace attributes

Introduction
Seismic data are one of the essential tools for identifying hydrocarbon reserves and developing reservoirs because of its spatial continuity nature (Nwaezeapu et al. 2019). A seismic reflection survey is required to obtain the seismic data to understand the subsurface's structure and stratigraphy (Hart 1999). For decades, the oil and gas industry has been using this seismic reflection technology to identify different prospects and ideal places for drilling wells for production (Yao et al. 2018). The seismic survey begins with a geoscientist's quest to image subsurface features. These requirements will provide the idea of required survey parameters, fold, shooting direction, etc. A seismic survey can be either two-dimensional (2D) or three-dimensional (3D). Generally, 2D/3D surveys can be chosen based on the subsurface information requirements to image the target depth (Le et al. 2019).

For few decades, the seismic method has been used to explore reservoirs by mapping the structural and stratigraphic information. The seismic reflection technique uses a receiver network to record their refraction/reflection arrivals due to impedance variation distribution as elastic waves propagate through the ground. Last few decades, 3D seismic surveys have become an essential tool in exploring and exploiting hydrocarbons. In the late 1970s, the first 3D seismic surveys were carried out but became widespread in the early 1990s (Stone 1994). The 3D seismic survey design mainly concentrated on bin analysis, fold, offset distribution, and azimuth distribution (Vermeer 1998). In seismic acquisition activities, the main agenda of seismic exploration is to image the seismic target with proper resolution. A group network of receivers (geophones/hydrophones) is placed in the land data acquisition to record the ground vibrations generated by active seismic sources such as explosives and vibrators. These geophones are deployed using predefined survey parameters such as spacing between receivers and the number of geophones in a single line for the 2D seismic survey and more than one line for the 3D seismic survey.

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Usual seismic survey design starts from analyzing critical information of subsurface in the acquisition area such as maximum target depth, target thickness, maximum geological dip (if not virgin area) (Galbraith 1994). Based on the requirements, minimum fold requirements will be calculated. The critical acquisition parameters such as receiver group interval, source interval, the maximum offset, bin size, active channels, number of receiver lines (for 3D), number of shots in a salvo (for 3D), and type of spread (symmetric or asymmetric). The survey design concentrates on achieving the regular offsets and good azimuthal coverage at each bin using selected acquisition parameters. In the conventional approach, quality control is qualitative only, and it just relies on the offset distribution and azimuthal distribution of surrounding CMP bins (Stork 2011). On the target surface/depth, the offset distribution and azimuthal distribution of a bin are ignored. The conventional acquisition parameters are based on the common-midpoint method, which uses the horizontal layer concept without considering lateral and vertical subsurface variations. However, none of these are valid in the entire field of acquisition. As a result of these assumptions, the acquired data may have significant footprints, and there is no guarantee of uniformity in the target surface/zone illumination (Mahgoub et al. 2012).

The general practice of designing seismic survey parameters assumes that the subsurface comprises horizontal layers of constant velocity and density. Based on this concept, a collection of source-receiver geometries has been used for understanding the coverage in the acquisition area (Xia et al. 2004). The range of target depths and dips, maximum and lowest propagation velocities, and desired fold of coverage are the only parameters included during the design process. The fundamental assumption of flat horizontal layers ignores the complexities frequently present in subsurface layers in high oil exploration or production interest regions (Evans 1997). However, the conventional survey designing process ignores these complexities. In conventional geometry analysis, seismic survey parameters are evaluated only on surface attributes, providing uniformity in fold coverage and regularity in offset distribution (Shukla et al. 2014).

Geometry parameters generated using traditional methods might be subjected to an optimization issue (Li and Dong 2006). With the growing interest of geoscientists in high-quality subsurface images, seismic data acquisition planning should focus on, and the geometry preparation should meet all acquisition targets. The success of every oil or gas exploration hinges on the design of the 3D seismic survey (Mondol 2010). In complex geological settings, studies related to optimizing and assessing seismic survey parameters for target depth play a key role in petroleum exploration before the actual acquisition (Liu et al. 2005). When dealing with complex structures, traditional methods for defining 3D seismic survey parameters are insufficient. Acquisition parameters in a seismic survey to be effective, appropriate illumination of the target zone should be reached. However, an ideal seismic survey design not only fulfills this condition but requires comfortable acquisition logistics with the lowest probable cost.

The solution for these issues may be addressed by evaluating each geometry and comparing the target surface results. Illumination maps can be created at the target reflectors for each of a few competing geometry templates, with the best one chosen by a qualitative evaluation of those maps. Over the years, 3D seismic ray modeling has become an operational tool for studying subsurface illumination in seismic studies (Saffarzadeh et al. 2018). A preferable procedure would be to begin with a subsurface structural and velocity model and utilize it to prepare/finalize acquisition settings. However, we do not have a complete subsurface model at the time of acquisition; otherwise, we might not have needed to acquire the data at all. The required information for the preparation model may get from earlier seismic data studies, from well logs, from geological interpretation, from any other conceptual geological model, from a combination of all of these.

Ray-trace modeling studies are one way to model the target zones and illumination of the target surface. These ray-trace methods provide the theoretical travel times and amplitudes between source and receiver through the model. Ray-trace modeling studies can have comprehensive scope studies such as survey planning and assessment, synthetic seismogram generation, velocity inversion, wave propagation studies, and 4D analysis. Rahimi Dalkhani et al. (2018) used perfectly matched layers and absorbing boundaries to evaluate finite & spectral element modeling techniques. The advantage of ray-trace modeling is that it allows geoscientists to access different scenarios and analyze the impact of various parameters on the quality of seismic illumination. The acquisition geophysicist can optimize the survey parameters associated with technical and financial constraints (Lines and Newrick 2004). Many researchers have contributed to various studies in accessing the acquisition parameters using modeling studies before actual acquisition. Suarez (2004) employed seismic ray-trace modeling studies to assess 3D seismic survey design to give a better image and optimize acquisition parameters for various surveys. de Oliveira et al. (2009) were applied ray-trace modeling techniques for accessing marine acquisition parameters by illumination maps. Zühlsdorff et al. (2020) explained practical benefits of ray-trace modeling studies in geometry evaluation. Zühlsdorff and Drottning (2013) planned a survey design for VSP using ray-trace approaches. A comprehensive discussion on illumination analysis and different levels measurements was discussed by (Xie et al. 2006). Lecomte et al. (2009) applied modeling studies for illuminating target horizons to access the designed seismic surveys.
Paraschivoiu (2016) has worked on crooked line effect on the illumination of subsurface after data acquisition. In the present study, we utilized ray-trace modeling to evaluate the seismic acquisition parameters in KG Basin, India. For this study, we have considered the stratigraphic heterogeneity in subsurface geology in terms of velocity, density, and structural complexity found and designed by horizons. Illumination maps were generated on the target surface and compared. By this comparison, seismic ray-trace modeling studies can test the acquisition parameters of geometry for the target objective, especially in complex reservoirs. This paper has assessed a 3D seismic acquisition survey design using ray-trace modeling techniques through illumination maps.

**Methodology**

This study used ray-trace modeling to estimate seismic acquisition parameters in heterogeneity medium using NORSAR modeling software. As part of this study, elastic earth was generated using strati and structural interpretation information like horizons, interval velocity, and density. The theoretical seismic waves were created using the wavefront construction (WFC) technique to travel into the elastic earth model by a 3D seismic acquisition design (Chambers and Kendall 2008). From these theoretical wavefront rays, we generated ray attributes (travel times and amplitudes). The illumination maps were created on the target horizon/depth by ray attributes to analyze the effect of the seismic acquisition parameters. Synthetic seismic shot gathers were generated for every shot using the seismic ray attributes in the seismic survey and applied general processing sequence on shot gather to get migrated post-stack section. This synthetic post-stack migrated section was compared to the previous survey’s post-stack migrated section and the brute stack section of the selected seismic survey.

**Ray-tracing modeling**

In seismic acquisition, ray shooting and bending are the traditional methods that simulate the seismic acquisition parameters. Nevertheless, these methods are time-consuming due to calculating only a single ray between the shot and receiver. In this application, the WFC method generates the mathematical seismic rays for generating the illumination maps and synthetic data to evaluate the survey design and parameters on the target horizons in heterogeneous subsurface (Cerveny 2001). The WFC method is flexible to estimate seismic modeling attributes by maintaining uniform ray density concerning wavefront propagation. The WFC technique works on the concept of asymptotic, high solution from the elastodynamic equation (Babich and Kiselev 1989).

These ray-trace modeling (WFC) studies are an approximation of high frequencies in seismic wave propagation.

**Model preparation**

The important part of seismic modeling studies is preparing the most realistic model analogous to the subsurface inhomogeneities. Previous interpreted information such as different structural horizons and varying vertical velocity and density uses a subsurface model for seismic wave propagation (Astebol 1994; Vinje et al. 1999). The model contains different blocks with specific material properties (density and velocity) separated by interfaces. Each interface structurally followed the pre-interpreted horizons and internally developed a triangular network with many nodes. The triangular representation of interfaces provides smoothness for an approximate solution on WFC ray-tracing interfaces, requiring first and second derivative smoothness. The explicit discontinuity between the blocks in the subsurface model requires applying Snell’s law during the seismic wave propagation (Vinje et al. 1993b). Figure 1 shows the triangular framework of the interface (Black) and theoretical ray network of the wavefront from source by WFC (white).

**Wavefront construction Method**

The WFC method was applied in 2D models (Vinje et al. 1993a) and later adopted for 3D models (Vinje et al. 1993b, 1999).
In the WFC method, the ray field generates by propagating wavefront step by step other than the ray concept as in conventional methods. The wavefront is generated step by step in time to maintain a uniform density of rays (Coman and Gajewski 2001). It means that the entire wavefront is moved a one-time step forward through the model for creating a new wavefront. The uniform ray field is not able to maintain in ray shooting and ray bending methods. So, the WFC method controls the divergence between the rays (Vinje et al. 1999).

The main essential steps in the WFC method are the creation of a primary WF, the transmission of WF in model with one-time step, maintain the uniform density of rays on the WF, creation of new rays at beyond the predefined limits of distance and angle, attributes estimation at a receiver such as travel time and amplitude. The WF topology is named connection points between WFs and ray field (node) and interior connecting lines. The triangle framework of WF topology is shown in Fig. 2. These triangle frameworks are able to stretch and twist while transmitting through the model. The triangle framework can be made relatively simple in propagation, interpolation, and approximation of the receiver’s attributes.

Each node of WF topology is at time \( t \) defined by its position, direction from source, wave type, normal, and dynamic properties of each ray. With the assistance of these parameters of nodes in WF at time \( t \), new WF can create at time step \( \Delta t \). So, a new wavefront has been created at \( t + \Delta t \). The information at two times \((t, t + \Delta t)\) will create new rays and calculate the ray attributes at the receiver location. The WF creation in successive time intervals with generating new triangles for all sides is shown in Fig. 3. The new triangles created and interpolated new rays based on distance excess than the limit of maximum distance \( (DS_{\text{max}}) \) and angular distance \( (DA_{\text{max}}) \) between rays. The wavefront ray can be reflected and transmitted at interfaces in the model where the same characteristics of the triangles network are available (Rueger 1993).

Gjoystdal et al. (2002) explain the procedure of the estimation of arrivals at each receiver. There is a need to modify the attributes from the propagating WF to find the parameter information at receivers. The ray cells are generated from the volume between the old WF and the new WF. These ray cells connected the old & new WFs through the triangle and three rays, which are the boundaries for ray cells. A box was created with the ray cell’s complete information using these six boundaries of the ray cell. The ray cell, along with...
a receiver shown in Fig. 3b. Coordinates of ray cells found the arrival information such as amplitude and travel time details of a receiver within the ray cell. These coordinates such as barycentric coordinates \((u, v)\) and travel time information \((t)\) at the ray cell. The information on travel time and amplitude at the receiver can be used for computing the synthetic seismogram. In this study, a synthetic seismogram is generated based on the 1D convolution modeling equation. The convolution of subsurface earth reflectivity creates a time-domain seismic trace with a wavelet or time series. The ray-tracing method produces synthetic seismograms and simulates time migrated sections by the concept of image ray (Gjøystdal et al. 2007; Lecomte et al. 2015).

**Illumination study**

In this study, the efficiency of seismic survey design has been assessed by illumination techniques in imaging the acquisition object (Moldoveanu et al. 2003). These illumination techniques can also be used in seismic data processing to understand acquisition-related amplitudes changes or shadow zones (Laurain and Vinje 2001; VerWest et al. 2001). A general definition of illumination in optics and light theory is "surface intensity of light." However, the geophysical definition is the seismic wave energy falling and reflected on a reflector (Sheriff 2002). The illumination studies are primarily used to generate illumination maps (hit maps) to understand the feasibility of the seismic acquisition design (Sassolas et al. 1999). These illumination studies provide quantitative analysis to reducing the risk of seismic exploration. With the help of the illumination on the target horizon, the acquisition parameters can be assessed, modified, or simply rejected. If we design and implement in the field without prior analysis that has a high chance of missing the objective and also increasing the high cost (Cain et al. 1998).

The binning methods are the most common illumination studies in the industry. Ray-based binning methods are fast and flexible and valid for high-frequency waves. The results of ray-tracing on the target surface are used to generate maps for analysis. These analyses can help acquisition geophysicists understand the regions having the high reflection points fall and low reflection fall regions (shadow areas) on the subsurface target depth for a specific acquisition geometry. The illumination maps (hit maps) provide information about hits (reflection points) in each cell of the target reflector (Bear et al. 2000).

In conventional techniques, a grid is defined based on the flat surface for creating the CMP fold maps, and the earth’s geometry and elastic properties are assumed uniform. However, in reality, it is no more valid. In the highly complex areas, hitting the reflections lead to uneven illumination on the target reflector. However, the earth subsurface is not uniform, and in such cases, conventional survey design methods lead to an inaccurate picture of the subsurface illumination (Hoffmann 2001; Campbell et al. 2002). Instead of the conventional CMP fold method, planning and designing the seismic acquisition parameters based on the illumination on target surfaces is the most appropriate method. Figure 4 explains information collecting from the target surface to create illumination maps.

**Application**

The wavefront construction is based on the ray-tracing modeling method used for assessing the seismic acquisition parameters to verify if accurate delineation of the subsurface is possible or not. The ultimate aim of the seismic data exploration is to image the subsurface targets by providing high-quality data concerning all limitations in surface & subsurface and financial limitations. Here, the first illumination maps (hit maps) and the post-stack migrated section assess the seismic acquisition parameters. The illumination maps of two acquisition geometries have been compared, and post-stack migrated sections of synthetic seismic data
and previous seismic data with a brute stack of present seismic data to verify the seismic acquisition design.

In this study, the methodology consists of a workflow to assess the seismic survey parameters. It follows as design the seismic survey, prepares a subsurface elastic model, generates ray attributes in the model by seismic acquisition parameters, creation & compared the illumination maps of different surveys, generation of the synthetic seismogram, applied seismic processing to synthetic seismic shot gathers, and compared the synthetic results with post-stack migrated sections.

We have used two geometries for this study. Geometry 1 was acquired a few years back in this area, which did not provide sufficient resolution on the target depth (Horizon-5) for interpretation. Geometry 2 is the present proposed one to illuminate the exploratory objective. The seismic acquisition parameters of these two surveys have shown in Table 1. The CMP fold of the two geometries is shown in Fig. 5a and b.

The first stage of this methodology is creating a subsurface elastic model with provided horizons and properties of blocks/layers such as interval velocity and density. The subsurface model is divided into blocks, and each block has its isotropic properties. The parameters used for preparing the model showed in the following Table 2. Figure 6 shows the block view and interface view of the model. This model has been finalized based on significant undulations observed on Horizon-4 and Horizon-5. Structurally, it is an essential portion to illuminate in this acquisition area. Most of the wavefield energy dispersed on Horizon-5, and many shadow zones (low illumination areas) have been identified. To improve illumination on Horizon-5 is the primary goal for new acquisition parameters.

Table 1 Seismic acquisition Parameters of Geometry 1 and Geometry 2

| Parameters              | Geometry 1 | Geometry 2 |
|-------------------------|------------|------------|
| Bin size                | 20 × 20    | 20 × 20    |
| Receivers per line      | 224        | 224        |
| Group interval          | 40         | 40         |
| Shot interval           | 40         | 40         |
| Receiver line interval  | 280        | 280        |
| Shot line interval      | 320        | 320        |
| No. of receivers lines  | 16         | 22         |
| Active channels per template | 3584    | 4928       |
| Shots per template      | 56         | 77         |
| Total fold              | 112        | 154        |
| Roll over               | Half Swath Roll | Half Swath Roll |
| Total no. of shots      | 25,872     | 25,872     |

Table 2 Subsurface elastic model properties

| Interfaces (blocks)       | P-Velocity (k/s) | Density (kg/m³) |
|---------------------------|------------------|-----------------|
| Surface-Horizon-1         | 1.6              | 1.5             |
| Horizon-1-Horizon-2       | 2.3              | 2.2             |
| Horizon-2-Horizon-3       | 2.5              | 2.1             |
| Horizon-3-Horizon-4       | 2.9              | 2.2             |
| Horizon-4-Horizon-5       | 4.1              | 2.2             |
| Horizon-5-Below           | 5.2              | 2.5             |

Fig. 5 Common Mid-Point fold: a Geometry 1 and b Geometry 2
at source position, type of reflection/transmission, and specific type of conversion at the model’s interface. Generally, a ray path is defined as the source to target and target to the receiver. The P-wave to P-wave conversion ray code is used in this study at all five interfaces of the model.

Once defined all instructions for ray field propagation at all interfaces in the model, the seismic wavefield has been transmitted using the application of the common-shot wavefront tracer of NORSAR Modeling software (Lecomte et al. 2015). The theoretical WF propagates by time step 100 ms for creating new WF and developing the new triangles in the WF network with maximum interpolated distance ($D_{\text{max}}$) of 300 m and maximum angular distance ($D_{\text{max}}$) of 5° between the rays. Figure 7 shows the seismic ray transmitting through interfaces in the model.

The ray-trace modeling produces ray striking points on the target surface, amplitude, travel time as ray attributes. These attributes are used for generating the illumination maps and synthetic shot gathers. The number of hits per bin is the hit count represented as hit maps that are used for the preliminary assessment of the seismic survey. Then the reflection coefficient of the model used to generate the synthetic shot gathers and applied the basic seismic processing steps to develop the post-stack migrated section.

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**Fig. 6** Subsurface model a Model block view b Model interface view

**Fig. 7** Ray-traces transmission at interfaces
Results and discussion

A seismic acquisition geophysicist desires to provide the quality data with respect to surface and subsurface limitations and financial constraints (Saffarzadeh et al. 2018). This study evaluated the seismic geometry parameters through the illumination maps and comparison of processing seismic migrated sections of synthetic data and real seismic data. Figure 8 shows the illumination maps (hit maps) of the target horizons produced by two types of seismic parameters. The Horizon-5 was considered as target of interest in the model (Fig. 6). The illumination maps of horizon-5 by Geometry 1 & Geometry 2 shown in Fig. 8.

Figure 8a shows illumination maps generated by Geometry 1 which leaves many areas with poor illumination especially in the undulation zone. An illumination map idea is based on the reflected points from target surface. The undulation zone has shown improved coverage with the new survey parameters. Figure 8b shows that the new seismic acquisition parameters fill the illumination holes on Horizon-5. The difference between these illumination maps is observed mainly in the undulation area marked by an arrow (Fig. 8).

The basis processing steps applied to synthetic shot gathers to generate migrated seismic sections by this methodology. Figure 9 shows the processing section of synthetic seismic data generated by the NORSAR modeling software. It has proved that the processing stacked seismic section.

Fig. 8  a Hitmap generated by the Geometry 1 and b Hitmap generated by the Geometry 2

Fig. 9  The post-stack migrated seismic section of synthetic seismic data generated by Geometry 2
using the PARADIGM Echo’s processing software shows better illumination in the basement. We understand that the present survey can illuminate the target depth (Horizon-5) very clearly from this section. Figure 9 is compared with Fig. 10b, which is the stacked section of real field data. It clearly understands that new acquisition parameters have achieved and reached seismic energy to horizon 5 in theoretical and real-time acquisition mode. Figure 10a and b show the original processing sections surveyed by the Geometry 1 (old-new parameters) and the brute stack of the present survey data (new survey parameters). This comparison shows that new seismic data acquisition has been illuminated quite better than old geometry, especially the seismic data events after the 1.7 ms.

The above results (Figs. 8 and 9) have substantiated that ray-tracing modeling can help choose and verify seismic survey designs concerning objectives. Some observations have been made from the present study on selected acquisition parameters.

- The target surface area has been covered by new acquisition parameters (shown in table_1). It provided reasonably uniform coverage within the full fold boundary (black color).
- The post-stack migrated section of synthetic seismic data has given more confidence in new survey parameters.
- The preliminary processing section (Brute stack) of real field data (Fig. 10b) has proven that the results of the present methodology (illumination maps and synthetic data processed section) are validated.

Conclusions

The main goal of any seismic acquisition is to achieve the target depth with excellent illumination. The seismic parameters play a crucial role in the achieve this goal, especially in complex subsurface. In this paper, we assessed the acquisition parameters for understanding geometry effectiveness. Conventional geometry analysis methods are valid only in the ideal condition, such as horizontal and isotropic medium. The inhomogeneity of the subsurface has been considered while preparing the geometry and done the validation. In this present work, we have used the ray-based modeling tool to assess parameters of geometries based on the WF construction method using NORSAR modeling software. A 3D subsurface model has been constructed to generate illumination maps and synthetic seismic shot gathers. The illumination maps (hit maps) have been compared and analyzed to understand the coverage of each geometry. Then compare the final migrated section of previous acquisition parameters (Geometry 1) with the brute stack of Geometry 2 to understand the imaging ability of Geometry 2. Finally, the ray-trace modeling studies having the ability to evaluate the seismic acquisition parameters for better imaging and also for cost-driven decision.

Finally, comparing the illumination maps of geometries can give us a quick understanding of geometry effectiveness. Furthermore, the comparison of processing sections of synthetic data provides confidence in the effectiveness of geometries. Therefore, seismic acquisition modeling methods helping in finalizing a geometry for illuminating target depth. Moreover, these ray-trace methods can also...
help in optimizing the seismic acquisition parameters and cost-driven decisions.

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Data availability All relevant data are available in the manuscript. No other data have been used.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest. The author declares that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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