REVIEW OF RAY THEORY APPLICATIONS IN MODELLING AND IMAGING OF SEISMIC DATA

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ABSTRACT

Throughout the last twenty years, 3D seismic ray modelling has developed from a research tool to a more operational tool that has gained growing interest in the petroleum industry. Various areas of application have been established and new ones are under development. Many of these applications require a modelling system with flexible, robust and efficient modelling algorithms in the core. The present paper reviews the basic elements of such a system, based on the 'open model' concept and the 'wavefront construction' technique. In the latter, Červený’s dynamic ray tracing is an intrinsic part. The modelling system can be used for generating ray attributes and synthetic seismograms for realistic 3D surveys with tens of thousands of shots and receivers. Moreover, some other types of application areas are illustrated: Production of Green’s functions for prestack depth migration and hybrid modelling (combined ray and finite-difference modelling), attribute mapping and illumination analysis, both for survey planning and interpretation. Finally, the concepts of ‘isochron rays’ and ‘velocity rays’ related to seismic isochrons have been introduced recently, with very interesting future applications.

1. INTRODUCTION

Twenty years ago a small group of geophysicists at NORSAR started to develop a new software package, with the ultimate goal of simulating seismic waves in 3D geological models. Some activity on seismic modelling had also been performed prior to that time – some experiments had been done with various 3D model representation techniques, and the first 3D kinematic ray paths had already been tediously calculated by the old IBM 360 and drawn on the shaky drum plotter. But at that time, the amplitudes were absent.

The new software project was sponsored by the service company Geco (at that time ‘the Geophysical Company of Norway’), having ambitions of becoming a technology leader on seismic acquisition, processing, and interpretation, and clearly seeing the need for an advanced tool in 3D modelling. In particular, the growing development of 3D seismic interpretation stations throughout the eighties made the way short to the construction of 3D models. This potentially short link between interpretation and modelling, with the possibility of integrating velocity estimation (e.g. tomography) and time-to-depth conversion (map migration) in the process, was one of the main motivations.

From the very beginning it was quite clear that the wave simulation method on which the new modelling system was to be built, would have to be ray tracing. With the

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computer speed in those days, ray techniques were in fact the only practically applicable ones in general 3D structures, and, even more important, these techniques possessed a number of properties that were perfectly suited for integrating modelling and interpretation: the ability of calculating the wave field as labelled ray contributions (or events), where event attributes like traveltimes, amplitudes, incident angels, etc., could be obtained in an explicit manner. In addition, the attributes could serve as a basis for generating ray theoretical seismograms, which e.g. could be used for evaluating and testing of 3D processing schemes. The advantage of being able to explicitly extract the various wave propagation effects, like geometrical spreading factors, reflection/transmission effects at interfaces, phase changes at caustics, splitting in various branches, P- and S-wave modes, etc., was very much appreciated. Another important characteristic of the ray method is the ability to locate the propagation of energy in the model, making the method particularly suited for applications in tomographic inversion. Moreover, the intuitive nature of ray tracing to visualize wave propagation would make such a modelling system an ideal ‘educational tool’, in order to better understand the complex features of seismic reflections in 3D complex media.

Two basic issues were strongly addressed in the first specification and design phase of the 3D seismic modelling system:

− a general and flexible model representation scheme for the 3D structural (layered) model with seismic properties, and
− an efficient ray tracing algorithm that could be integrated with the model representation, calculating both the kinematic and dynamic properties of the wave field along various ray paths between given source and receiver positions.

With respect to the first issue, it very soon became clear that we had to start more or less on scratch. No published methods were found that met our needs, even if some ideas could be obtained from the relatively new area of 3D computer graphics.

With respect to the second issue we were far luckier. In our earlier experiments we had used theory from the book of Červený et al. (1977), e.g. for coding the reflection/transmission coefficients at an interface, and later Červený and Hron (1980) turned out to be a major reference. The formulation of their dynamic ray tracer fit perfectly into our modelling scheme, and contained all the necessary ingredients we searched for: calculation of rays as well as ray attributes like wavefront curvatures and amplitudes along the rays, including both the travelling through the continuous properties of the layers and the conversions at the model interfaces. The methods were clearly and explicitly formulated, so the way from the mathematics to computer code was mostly straightforward. In particular the ray-centered coordinate system was very appropriate to use and easy to implement. It is true to say that these basic works of Červený (and of course also later works) formed one of the key elements for our work with modelling software throughout the following twenty years. Even after converting from single two-point ray tracing in the eighties to the wavefront construction technique in the nineties, Červený’s formulas still constitute the very ‘heart’ of the system.

Until some few years ago we had to realize that the use of 3D seismic modelling as an industrial tool was rather limited. Throughout the eighties most applications of our modelling systems were devoted to R&D topics, such as producing synthetic 3D data for