QUADRATIC NORMAL MOVEOUTS OF SYMMETRIC REFLECTIONS IN ELASTIC MEDIA: A QUICK TUTORIAL

M. TYGEL AND L.T. SANTOS

Department of Applied Mathematics, IMECC, State University of Campinas (UNICAMP), CP 6065, 13081-970, Campinas (SP), Brazil (tygel@ime.unicamp.br)

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ABSTRACT

The design of reflection traveltime approximations for optimal stacking and inversion has always been a subject of much interest in seismic processing. A most prominent role is played by quadratic normal moveouts, namely reflection traveltimes around zero-offset computed as second-order Taylor expansions in midpoint and offset coordinates. Quadratic normal moveouts are best employed to model symmetric reflections, for which the ray code in the downgoing direction coincides with the ray code in the upgoing direction in reverse order. Besides pure (non-converted) primaries, many multiply reflected and converted waves give rise to symmetric reflections. We show that the quadratic normal moveout of a symmetric reflection admits a natural decomposition into a midpoint term and an offset term. These, in turn, can be formulated as the traveltimes of the one-way normal (N) and normal-incidence-point (NIP) waves, respectively. With the help of this decomposition, which is valid for propagation in isotropic and anisotropic elastic media, we are able to derive, in a simple and didactic way, a unified expression for the quadratic normal moveout of a symmetric reflection in its most general form in 3D. The obtained expression allows for a direct interpretation of its various terms and fully encompasses the effects of velocity gradients and Earth surface topography.

Key words: quadratic traveltime, NMO, symmetric reflections

1. INTRODUCTION

Expressions that are able to model the traveltimes of selected events in a most practical and direct way have always been of key interest in seismic data processing. As a rule, for a given event observed at a given reference trace, such modeling expressions, referred as moveouts in the seismic literature, try to simulate the traveltimes of that event as the traces move away from the reference one.

Since the pioneering works of Dix (1955) and Taner and Koehler (1969), different approximation formulas for the traveltimes were developed, generally based on second- and fourth-order Taylor expansions in offset, considering a common-midpoint (CMP) configuration and non-converted waves. All these formulas are essentially valid for small or moderate offsets and are used to simulate a stacked ZO section. Still within the CMP
configuration, moveouts based on continued fraction expansions have been designed to account for large offsets and anisotropic effects (Tsvankin and Thomsen, 1994; Alkhalifah, 1997,2000; Pech et al., 2003,2004; Fomel, 2004; Ursin and Stovas, 2006). Similar expressions, however with a different interpretation of the non-hyperbolic coefficients, have been also used in Sayers and Ebrom (1997) for the analysis of traveltime in azimuthally anisotropic media. For a comprehensive exposition of reflection moveouts in CMP geometry, we refer the reader to the monograph by Tsvankin (2001).

Recently, much attention has been given to moveout expressions that are not restricted to the CMP configuration. These include the classical quadratic moveouts (Ursin, 1982; Bortfeld, 1989; Schleicher et al., 1993), as well as the multifocus moveout (Berkovitch et al., 1994; Tygel et al., 1997; Gelchinsky et al., 1999).

The advantage of such moveouts in seismic processing is that they allow a full use of the available data for stacking purposes. Due to increased redundancy, images with a higher signal-to-noise ratio can be obtained. As described in Hubral (1999), this is the main motivation of the so-called macro-model independent or data-driven seismic imaging methods. Once again, normal moveouts, in particular, quadratic normal moveouts, play a fundamental role.

We adopt the ray theoretical approach that characterizes each event as a ray of specific signature. In particular, the ray that specifies the event at the reference trace is called the reference or central ray. Rays of the same signature as the central ray and in its vicinity are called paraxial rays. With this understanding, for a given central ray, any moveout aims to model the traveltime variation of the paraxial rays relative to the traveltime of the central ray. For a comprehensive treatment of ray theory, the reader is referred to Červený (2001). For the basic theory and practical applications of seismic data processing, the reader is referred to Yilmaz (2001).

A common feature of all moveout formulas is that they are expressed in terms of a few parameters or coefficients that pertain to the central ray. These parameters relate to rates of change (derivatives up to a given order) of the traveltime with respect to the dislocations from the initial and endpoints of the central ray. The choice and number of moveout parameters depend on the specific purpose, e.g., modeling, imaging or inversion, to which it is designed.

The case, where the central ray is a zero-offset (ZO) reflection ray, plays a fundamental role in seismic processing. In this situation the central ray is a normal ray to the reflector and the traveltimes of paraxial rays are called normal moveouts. An extensive literature is devoted to this specific case with main interest on their various seismic imaging applications. In this context, second-order Taylor expansions of traveltime (generally called quadratic normal moveouts) are of particular importance.

1.1. Symmetric reflections

For a given target reflector, an elementary reflection such that its ray code from the source to the reflector coincides with the ray code of the ray from the reflector to the receiver in reverse order is referred to as a symmetric reflection. Considered as a function of midpoint and half-offset coordinates the traveltime of a symmetric reflection is an even function of half-offset. As a consequence, any power series expansion of the traveltime of a symmetric reflection with respect to zero offset (normal moveout) contains only even powers of offset. This condition is trivially realized for primary reflected waves with pure