Chapter 1

Introduction

Over time, seismic land data acquisition evolved from the recording of only the vertical component of the seismic displacement field to multi-component recordings. An increasing number of surveys for detailed qualitative subsurface-parameter studies uses multicomponent recordings. A three-component source, together with a three-component receiver, enables recording of the total elastic wave field. It is, theoretically, the most complete elastic measurement one can obtain from the subsurface for a given surface acquisition area. This chapter explains why a tensor wave field can be constructed from individual vector wave fields. The construction can be done successfully only when the vector source and receiver behavior does not vary throughout the data set. Using reciprocity principles for vector wave fields, I design an equalization scheme that removes non-reciprocal inconsistencies in the data. To test this method I use finite-difference modeling scheme that allows modeling of linear wave propagation as well as nonlinear wave propagation with nonlinear chaotic vector sources. Finally I convert scalar well log data into a tensorial well log from which I estimate better surface seismic velocities than the conventional Dix formula allows.

1.1 From scalar and vector to tensor wave fields

The total wave field is recorded only when three mutually orthogonal source directions are activated and recorded with three mutually orthogonal receiver components (Figure 1.1). The activation of only one three-component source results in the recording of a vector wave field. If this experiment is repeated with three source orientations that are orthogonally oriented to each other, the three separate experiments can be combined into a tensor wave field. Such a tensor wave field can be seen as a unit of three identical orthogonal experiments, which completely span the space of all possible elastic experiments for a given observation point. Equation (1.1) states mathematically the relation between two vector wave fields and the associated tensor wave field:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} (\mathbf{r}_s, t) \quad * \quad \begin{bmatrix} x & y & z \end{bmatrix} (\mathbf{r}_g, t)$$
$$= \begin{bmatrix} Xx & Xy & Xz \\ Yx & Yy & Yz \\ Zx & Zy & Zz \end{bmatrix} (\mathbf{r}_s, \mathbf{r}_g, t) \tag{1.1}$$

Equation (1.1) establishes the notation that I will use throughout this thesis. Here all upper case letters relate to the components of the source vector, while all lower case letters relate to the components of the receiver vector. I construct a 3×3 tensor by taking the outer product of two vector experiments. In matrix notation, the tensor elements connect a given source component with a particular receiver component. $\mathbf{r}_s$ is the source point and $\mathbf{r}_g$ the location of the receiver in space, while t denotes the recording time axis. A wave field with any source and receiver vector orientation can be formed from this tensor experiment and, additionally, the wave field obeys the rules of tensor transformations.

To process such a tensor wave field, one has two fundamental choices: the first is to devise new algorithms to process this kind of new vector wave field data. This would usually entail modifications to existing vector wave field algorithms. The second is to decompose tensor wave fields into scalar fields, called eigenfields. This would have the advantage of a vast array of existing well-known scalar algorithms, which could be used for processing. Whichever route is chosen, one must begin with the premise that the starting data set is a true tensor wave field.

In this thesis, I show tensor wave fields generated by means of conventional surface seismics experiments. However, tensor fields can also be found in other applications. For example, in Chapter 7, I convert well log to a tensorial log and outline several advantages of converting three related scalar quantities to a tensor field. The application of tensor fields allows one to transcend the traditional boundaries of well log and surface seismic measurements, allowing a reconciliation of observations on different scales.

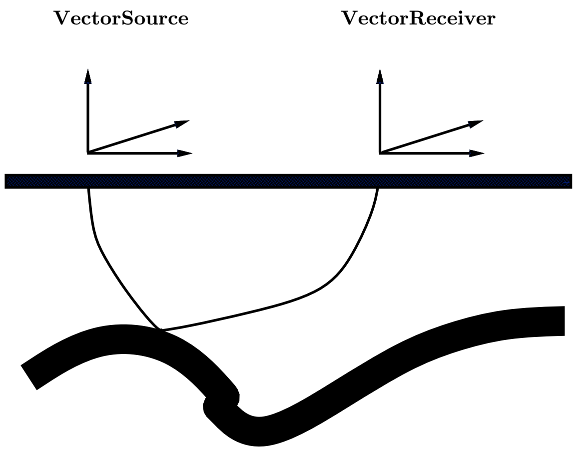

FIG. 1.1. Schematic representation of a multi component experiment. If the source is activated in three mutually orthogonal directions and the wave field is recorded in three mutually orthogonal directions with an identical source, a tensor wave field is obtained. intro-experibw [NR]

1.2 Tensor wave fields and elastic inversion

Theoretically, the results of elastic inversion depend directly on the completeness of the seismic data set for a given observation area. Primary considerations for completeness are bandwidth of the seismic signal used, spatial and temporal adequate (unaliased) sampling, and proper sampling in shot and geophone space. If some of those conditions are weakened, one has to resort to filling incomplete data or model spaces explicitly, as Claerbout (1992, 1994) suggests, to get meaningful inversion results. The recording of three orthogonal displacement components and the use of three orthogonal source components should increase the information content that one is able to extract from the data set. If one wants to extract structural information only, one can apply conventional scalar processing techniques, disregarding interrelationships between source and receiver components. If one wants to be more ambitious and aim for the determination of rock properties (elastic parameters), one has to consider carefully the coupling between those components. However, these components can only be compared when they are generated uniformly. In the case of sources, it means that one would like to reproduce identical source behavior at each source location. One would like the same for the receivers. In reality, this is not likely to be case; in the data set I use in this thesis, source and receiver behavior vary strongly from location to location and also from component to component. In Chapter 2 I show a brief analysis of source and receiver variations in a nine-component seismic data set.

1.3 Multi-component sources

A source is, in general, a nonlinear device, since it has to deliver a large enough elastic disturbance to allow recording of signals diffracted from objects at depth. In land data seismic acquisition, the three-component source is placed on the earth's surface. When activated, the source interacts with the free surface and radiates energy as a coupled system (Stam, 1990). The usual point source approximation breaks down and energy is radiated from the source non isotropically, even when the interaction is a completely linear process. The source will most likely behave in a nonlinear manner when interacting with the earth's surface; however, not much is known about nonlinear interaction mechanisms. Moreover, the radiation characteristic can differ from source component to source component. In the real world the free surface interaction can change from source point to source point depending on the local material properties of the near surface. Variations in the source itself contribute to the variability of radiation patterns. In Chapter 5 I incorporate nonlinear effects in a finite-difference wave propagation simulation and show that it is possible to model them efficiently. In Chapter 6 I solve the problem of suppressing differences in radiation behavior. After such an equalization process for the whole survey is done, one can process the data as if they had been produced by an equivalent average three-component source.

Routine processing of elastic data employs source and receiver rotations (Alford, 1986, Nichols, 1991) in order to maximize subsurface wave field stacks. Subsequently, all the well-known tools of conventional scalar processing can be used. When sources or receivers show different behavior that depend on the location, such a stacked energy maximization will tend to give less useful results. In addition, radiation pattern equalization, theoretically allows an improved elastic inversion —if the total wave field is recorded— by combining the recordings and forming a tensor wave field.

Bishop (1989) observed and presented source and receiver variations in multi-component data at the SEG research workshop on recording and processing vector wave field data. In his particular example, unequal radiation patterns show up in amplitude differences of cross-component stacks and, furthermore, severely influence the estimation of the principal axis of azimuthal anisotropy.

1.4 Symmetrizing a tensor wave field

The method I use in Chapter 6 for estimating and removing differential radiation characteristic is based on a fundamental property of the linear elastic wave equation. As explained in Chapter 4, it is the self-adjointness of this differential equation (Morse and Feshbach, 1953b), which shows itself in a property called reciprocity. Reciprocity for vector wave fields requires the result of the experiment to remain the same when both position and vector components of source and receiver are interchanged. Consequently, the data one collects at the earth's surface should be identical. Reciprocity holds if one operates with ideal sources and receivers, and if there is no noise present in the data. While experiments in laboratories (Knopoff and Gangi, 1959) show an excellent match between reciprocal data, experiments in the field show some mismatch between reciprocal trace pairs (Fenati and Rocca, 1984). This mismatch may be due to uncertainty in source and receiver positioning; it may also result from the fact that the source is not behaving identically at each location. Nonlinearities in the source-surface interaction, mispositioning, and noise prevent exact duplication of reciprocal data. If one assumes that noise is a random process with respect to the reciprocal experiment and that receivers respond reasonably isotropically, one can estimate the source-consistent differences in the data. Under this assumption, it is possible to set up the differential radiation characterization as a optimization process that minimizes differences in the reciprocal trace pairs. With each reciprocal trace pair, I estimate the combination of two differential radiation patterns: the one due to the source itself and the other due to the reciprocal source. Since I use the principle of reciprocity, the field experiment has to be carried out in a reciprocal manner: at each source position we needs a receiver position and the total wave field needs to be recorded for those locations.

The advantage of estimating differential behavior before stack is that the only operational principle used is reciprocity. One does not have to know anything about the structure or the subsurface properties in order to equalize the patterns.

1.5 Tensorial well logs

Well log measurements can be regarded as separate measurements of scalar quantities, such as P-wave and S-wave velocity and density. Vector wave field recordings measure individual vector quantities of a seismic wave field. Conventional processing of such data treats scalar or vector recordings as separate measurements. In this thesis I show that combining individual scalar or vector measurements into a general tensor quantity does not necessarily mean an increase in complexity. The newly created tensor quantity in such cases might look like a more complex quantity, but in practical terms it simplifies data processing and allows for more general and accurate algorithms.