Chapter 1

Introduction

This dissertation addresses the problem of interpolating irregularly spaced seismic exploration data to regular spatial locations. Geophysical fields are often measured on spatially irregular locations and need to be interpolated to a regular grid in order to be displayed, processed or interpreted. In atmospheric sciences, the problem of data estimation on a regular grid from observations at irregular locations is known as *spatial analysis* (Daley, 1991). The term *gridding* is accepted in the potential field community (Li and Gotze, 1999). In this dissertation, I adopt the term *data regularization* to address the same problem in the seismic exploration context.

MOTIVATION AND PROBLEM FORMULATION

Until recently, conventional seismic exploration techniques successfully escaped the problem of data regularization. Two-dimensional seismic exploration (seismic profiling) conveniently positions seismic sources and receivers at regular locations. Although the problem of missing data does occur occasionally (missing near offsets in marine surveys, dead or severely contaminated traces, etc.), it has only minor importance in 2-D data processing.

The rapid development of three-dimensional seismic methods in recent years has brought another spatial dimension to the acquisition patterns. In fact, the data dimensionality has increases by two, because both the source and receiver locations become two-dimensional variables in a 3-D seismic setting. The difficulty of acquiring regularly positioned data has become apparent. An ideal situation, where both sources and receivers are uniformly distributed on the surface, almost never occurs in the practice of 3-D exploration. In typical marine observations, receiver streamers are towed behind a vessel. This setting leads to an irregular offset-azimuth distribution. Furthermore, the regularity of midpoint distribution at large offsets is often affected by cable feathering. On land, there is more variety in observation systems, but uniform 3-D coverage is rarely achieved because of practical and economic constraints (Stone, 1994).

Figure 1.1 shows the common-midpoint (CMP) distribution for a selected range of offsets in a 3-D marine dataset, acquired in the North Sea. The CMP distribution looks fairly uniform, but the data irregularity becomes apparent if we consider an analogous plot for a selected bin in in-line and cross-line offsets (Figure 1.2). Such irregularities are fairly common in marine acquisition (Biondi, 1999). I use this North Sea dataset for testing data regularization techniques presented in this dissertation.

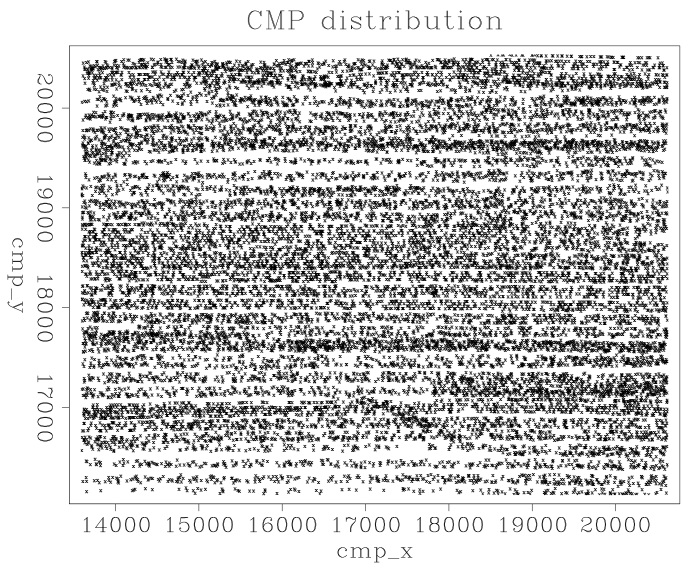

Figure 1.1: Midpoint distribution for a wide range of offsets in the North Sea dataset. intro-cmp-all [ER]

The problem of data irregularity in 3-D seismic exploration manifests itself in different situations. Some of them are

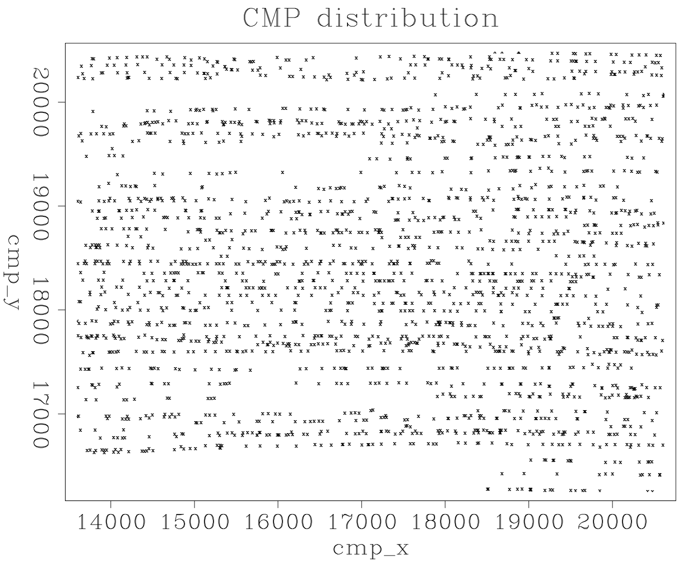

Figure 1.2: Midpoint distribution for a 50 by 50 m offset bin in the North Sea dataset. intro-cmp-win [ER]

- *Kirchhoff prestack migration*, the most popular method of 3-D seismic imaging, constructs the image by integrating the input data over both source and receiver locations (Bleistein, 1987). In practice, integration is replaced by summation over all available data. Data irregularities often transform into image artifacts (Gardner and Canning, 1994).

- *Multiple elimination* is an important processing task in many regions, where primary reflections are contaminated by multiples. Some of the most powerful methods of multiple elimination assume uniform distribution of sources and receivers (Weglein et al., 1997; Verschuur and Berkhout, 1997; Dragoset and Jericevic, 1998). Data regularization by interpolating missing data is a necessary step in extending these methods to 3-D (van Dedem and Verschuur, 1998).

- *Common-azimuth migration* is a powerful imaging method, tailored for narrow-azimuth marine acquisitions (Biondi and Palacharla, 1996a; Biondi, 1997). Its implementation suggested by Biondi and Palacharla (1996a) implies that the input data are regularly spaced in midpoint and offset coordinates and therefore relies heavily on preprocessing by data regularization. A similar situation occurs in offset plane wave migration (Mosher et al., 1997).

- *4-D seismic monitoring* compares 3-D images from repeated seismic surveys in order to monitor changes in the reservoir (Greaves and Fulp, 1987; Lumley, 1995). It often requires co-locating datasets with different acquisition geometries (Legott et al., 1999; Morice et al., 2000). Data regularization onto a uniform grid provides a method for accurate data matching.

It is important to note that one can use the output of data regularization consistently for different data processing tasks.

In this dissertation, I focus on a general approach to three-dimensional seismic data regularization. I address the following problem: given irregularly spaced data as input, produce a regularly spaced output that will preserve the essential features of the input. Although this is a well-known problem in some other Earth sciences (atmospheric sciences, potential fields, mining and petroleum engineering), two particular properties of seismic exploration data require special treatment. First, the extremely large exploration datasets prohibit computationally expensive methods and require algorithmic efficiency. Second, multiple coverage makes seismic data predictable in the offset direction, which can be additionally explored for optimal results.

The goal of this work is to develop a collection of efficient, practically affordable numerical methods for data regularization. The most optimal methods need to be specifically tailored for seismic reflection data to take advantage of the additional degrees of predictability that such data possess.

COMPARISON WITH PREVIOUS METHODS

Several methods of seismic data regularization appear in the geophysical literature and in the practice of seismic exploration.

One group of methods is based on different types of integral (Kirchhoff) continuation operators, such as offset continuation (Stovas and Fomel, 1993, 1996; Chemingui and Biondi, 1994; Bagaini and Spagnolini, 1996), shot continuation (Schwab, 1993; Bagaini and Spagnolini, 1993; Spagnolini and Opreni, 1996), and azimuth moveout (Biondi et al., 1998). Integral continuation operators can be applied directly for missing data interpolation and regularization (Bagaini et al., 1994; Mazzucchelli and Rocca, 1999). However, they do not behave well for continuation at small distances in the offset space because of limited integration apertures and, therefore, are not well-suited for interpolating neighboring records. Additionally, like all integral (Kirchhoff-type) operators, they suffer from irregularities in the input geometry. The latter problem is addressed by accurate but expensive inversion to common offset (Chemingui, 1999).

Another group of methods formulates data regularization as an iterative optimization problem with a convolution operator (Claerbout, 1992, 1999). Convolution with prediction-error filters is a popular choice for interpolating locally plane seismic events (Spitz, 1991). The method has a comparatively high efficiency, which degrades in the case of large data gaps. Handling non-stationary events presents an additional difficulty. Non-stationary prediction-error filtering leads to an accurate but relatively expensive method with many adjustable parameters (Crawley, 1999; Clapp et al., 1999).

Methods based on nonuniform discrete Fourier transforms (Duijndam et al., 1999; Hindriks et al., 1997) or Radon transforms (Thorson and Claerbout, 1985; Ji, 1994) have some attractive computational properties but do not outperform convolutional optimization methods and have serious limitations with respect to regularizing aliased data.

In this dissertation, I follow Claerbout's iterative optimization framework, extending it in several important ways. The major original contributions of this work are summarized below.

Contributions

1. Preconditioning by recursive filtering as a general method for accelerating the convergence of iterative data regularization.

2. A general approach to iterative data regularization using B-spline forward interpolation.

3. New choices for the regularization filters:

    (a) tension-spline filters for regularizing smooth two-dimensional surfaces,

   (b) local plane-wave-destructor filters for regularizing seismic images,

   (c) offset and shot continuation filters for regularizing prestack seismic data.

4. A comprehensive theory of differential offset continuation, which serves as a bridge between integral and convolutional approaches.

The most innovative part of this dissertation is the theory and practical implementation of differential offset continuation. The theory captures the intrinsic connection among different parts of seismic reflection data. The practical implementation transforms differential offset continuation into a local efficiently computed regularization operator.

OUTLINE

The dissertation is organized according to the following outline:

Fundamentals of data regularization

Theoretical fundamentals of this work are introduced in Chapter 2. I pose data regularization as an optimization problem and trace its statistical roots. The optimization objective consists of two parts: fitting the observed data with the forward modeling operator and "styling" the model with an appropriately chosen regularization operator.

Forward interpolation

Chapter 3 addresses the choice of the forward modeling operator. I discuss the general theory of forward interpolation and possible practical strategies. I identify B-spline interpolation as the most accurate forward operator among other similar-cost options.

Iterative data regularization

The practical aspects of data regularization by iterative optimization are discussed in Chapter 4. Considering two possible formulations of the optimization problem, I show that the data-space formulation (also known as model preconditioning) provides significantly faster convergence and exhibits more appropriate behavior at early iterations than the alternative, model-space formulation. I introduce preconditioning by recursive filtering and apply it in multidimensional problems with the help of Claerbout's helix transform (Claerbout, 1998a).

Choice of regularization and numerical results

Chapter 5 is the culmination of this dissertation. In this chapter, I focuse on the choice of the regularization operator and develop three possible strategies: tension splines, local plane-wave destruction, and offset continuation. Each of the strategies is appropriate for a particular kind of the regularized data. The performance of the proposed methods is tested and illustrated on several synthetic and real-data examples.

Offset continuation for reflection seismic data

Chapter 6 contains the theory of differential offset continuation. I introduce a partial differential equation for describing offset continuation as a continuous process and prove that, under certain assumptions, it provides correct kinematic and amplitude behavior for the continued data. I establish theoretical links between integral, differential, and frequency-domain operators by solving an initial-value problem for the proposed equation.

Conclusions

Chapter 7 completes the dissertation with a summary of the results and a discussion of the advantages and limitations of the proposed numerical methods.

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