R.K. Tiwari · R. Rekapalli

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R. K. Tiwari
CSIR-NGRI
Hyderabad, India

R. Rekapalli
CSIR-NGRI
Hyderabad, India

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Foreword

Recent advent of modern computer technologies and acquisition of huge data has made the data analyses and processing unavoidable for robust interpretations, not only in the earth sciences but also for various other branches of science. This inevitability requires knowledgeable, skilled, and proficient researchers who will be able to modernize, develop, and make anticipated advancement and progress in the underlying field to render precise interpretation of the geophysical data. This book demonstrates and discusses the singular spectrum-based algorithms for data-adaptive processing of seismic signals in time and frequency domains. Among different aspects of signal processing, the book mainly focuses on removal of undesired signals/noises which are not useful for physical interpretations of seismic data, time domain frequency filtering, data gap filling, and diffraction wave field separation. Drs. Tiwari and Rajesh provide comprehensive details of the up-to-date and advanced methodologies and have demonstrated the complete mathematical background, testing of the algorithms on synthetic data, as well as real-time example on 1D, 2D, and 3D field data with physical interpretation aided by regional geological as well as borehole data. In view of recent advances and necessity of computer coding, the authors have provided a chapter with simple MATLAB coding for singular spectrum analysis with simple examples. They have also incorporated useful materials on SVD computations with examples as appendix. This volume would serve as a liberal resource for understanding and practicing singular spectrum-based seismic data processing. Attempt has been made to comprehend the developments and application of singular spectrum-based methods in seismic data processing, and systematically up-to-date information have been put forth.

Virendra M. Tiwari

Director
CSIR-National Geophysical Research Institute
Hyderabad, India

Preface

Signal analyses and data processing have become unavoidable not only for geophysics but also for various other branches of science. This inevitability essentially requires knowledgeable, skilled, and proficient researchers who will be able to modernize, develop, and make anticipated advancement and progress in the underlying field to render precise interpretation of the geophysical data. The formulation of singular value decomposition (SVD) by Lanczos in 1961 led to the design and development of several SVD-based algorithms to decompose the data using data adaptive eigenvectors. The analysis of singular spectrum is a robust and promising method being used in the geosciences for trend and principal component analysis, filtering, data gap filling, etc. for over the past 50 years. These methods use the virtue of data adaptive-basis function for decomposing signals into linearly independent components of physical significance. The advances in these methods attracted the attention of several branches of geosciences (e.g., astronomical data gap filling; principal component and trend analysis of climate data; 2D, 3D, and 5D seismic data filtering; seismological data processing; gravity data processing; etc.) to improve the accuracy of interpretation.

In the beginning of singular spectrum-based seismic data processing, SVD was applied onto 2D seismic data matrix in time domain to suppress noise and multiples. The SVD decomposes the data matrix into eigen-weighted sum of orthogonal matrices of rank one, which are also known as eigenimages of data matrix. T-x SSA frequency filtering was developed for noise suppression, data gap filling, wave field separation, frequency filtering, etc. Employing fixed basis functions in conventional filtering of spatiotemporal nonlinear and non-stationary seismic data creates the artifacts. Therefore, singular spectrum-based data-adaptive decomposition using the eigenvectors of data as basic functions gained importance as an alternative to avoid artifacts. In view of this, several fast computational algorithms are also developed for the easy adaption of singular spectrum methods into the seismic data processing. In this book, attempt has been made to comprehend the up-to-date developments and application of singular spectrum-based methods for seismic data processing.

Beginning with the introduction to noises in seismic data, conventional and unconventional methods of denoising/filtering, and state-of-the-art information in the subject area, we have attempted to discuss the role of data-adaptive noise suppression in the reflection seismic methods in the first chapter. The time and frequency domain eigenimage and Cadzow filtering techniques are provided in the second chapter with complete description of algorithm and appropriate examples of filtering/denoising. Chapter 3 of this book deals with SSA-based time domain frequency filtering technique along with the eigen-weighted spectrum-based triplet grouping procedure as an alternative user-friendly method for filtering the non-stationary data to surmount the problems associated with filtering-related artifacts. The novelty of the method is discussed using synthetic data and then provided an example of its application to real data in comparison with conventional FFT-based filtering. The application of SSA on 2D seismic data in time and frequency domain is provided in the fourth chapter with illustrative examples demonstrating the basic difference between time and frequency domain applications in comparison with f-x deconvolution filter. Spatial/time slice SSA (SSSA/TSSSA) algorithm for noise suppression is discussed in Chap. 5 with testing on the synthetic data with different kinds of noises compared with f-x SSA and f-x deconvolution methods and an example case study from Durgapur, West Bengal, India. The accuracy of the denoised output is discussed, integrated with regional geology and litho-log data. In another case study, the method was applied to pre- and post-stack field data from Singareni coalfield, Telangana, India, to discuss the colored noise suppression and scattered primary amplitude recovery for accurate identification of intrinsic fault structures associated with coalfield.

Chapter 6 provides comprehensive details about the advanced methodologies: (i) optimized SSA for colored noise suppression for seismic reflection data, (ii) randomized SVD, (iii) factorized Hankel technique, and (iv) windowed SSA for fast and robust application of singular value decomposition over the existing conventional methods on synthetic and real seismic data sets. The seventh chapter is destined to present the methodologies of time and frequency domain applications of multichannel SSA for simultaneous seismic data denoising and gap filling. The methods are tested on 3D seismic synthetic data and applied to seismic post-stack data from Sleipner CO_2 storage site. The SSA-based 1D, 2D, and 3D data gap filling strategies are discussed in the next chapter. The detailed description of iterative frequency and time domain MSSA data gap filling strategies are discussed with appropriate examples. The influence of noise and comparative effectiveness of TSSSA over the multivariate wavelet method in deterministic wavelet estimation via generalized inversion is tested on synthetic data in Chap. 9. The singular spectrum-based noise suppression was tested to enhance the accuracy of horizon and 2D seismic data for geologically consistent geophysical interpretation in the tenth chapter. The basic definition and classification of attributes as well as the impact of noise-/processing-related artifacts on derived attributes are discussed in this chapter. Then, we compile appropriate synthetic and real data examples to discuss the role and necessity for singular spectrum-based pre-filtering in attribute studies. Finally, a MATLAB-based singular spectrum analysis tutorial is presented in the 11th chapter for beginner to start coding the singular spectrum-based algorithms for better and artifact-free processing of nonlinear and non-stationary geophysical data sets. The mathematical description, basic definition of eigenvectors, eigenvalues, and their physical significance, along with simple examples of SVD are provided as appendix for the use of beginners to understand the concept of SVD.

Hence, this book as a whole serves as an ample volume of the modern development and application of singular spectrum-based methods for the improvement of 1D, 2D, and 3D seismic data quality, thereby accuracy of interpretations. This book may also serve as a liberal resource for understanding and practicing singular spectrum-based seismic data processing algorithms of wide spectrum.

Hyderabad, India

R. K. Tiwari
R. Rekapalli

Acknowledgments

The book is based on singular spectrum-based analysis, a robust method for analyzing the time series data to separate linearly independent processes for physical interpretation. Over the past decade, there is a lot of advancement in its applications to various branches of sciences. Among these, singular spectrum analysis of seismic data laid the roadway for rank reduction-based denoising, data gap filling, filtering, and wave field separation. We wrote this book to provide an integrated material for understanding the time and frequency domain singular spectrum-based methods that have been developed and used for seismic data processing. We have tried to provide an unbiased coverage of the subject developments by the global research community. We would like to mention that in order to present unbiased integrated picture and self-sufficiency of the book, repetition of some material is inevitable.

There are some illustrations and mathematical descriptions taken from the work of various researchers which we have sincerely acknowledged. We, particularly, acknowledge the Society of Exploration Geophysics, Springer, Elsevier, Indian Geophysical Union, and Society of Petroleum Geophysicists, India, for using their figures modified after their published materials. We also acknowledge Dr. C. Lanczos, Dr. T.J. Ulrych, and Dr. S.R. Trickett for their pioneering contributions in the field of singular spectrum-based seismic data processing algorithms from which we have immensely benefited. We also acknowledge Dr. S.R. Trickett, Prof. Mauricio Sacchi, and Dr. Vicente Oropeza for further advancements in frequency domain singular spectrum-based methods for 2D and 3D seismic data. We thank Prof. Mrinal K. Sen, former Director, CSIR-NGRI, Hyderabad, India, for his support and encouragement.

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Contents

Chapter 1
Introduction to Denoising and Data Gap Filling of Seismic Reflection Data

1.1 Introduction

Seismic data is a mixture of several wanted (reflections, refractions) and unwanted (ground roll, diffractions, airwave etc.) signals. Different wave fields recorded by the seismic receiver can be seen from Fig. 1.1. Separation of wanted signal from such unwanted noises is therefore fundamental in geophysical signal processing. Especially, it is very difficult for a visual inspection to completely distinguish primary reflections and noise in the raw data of active seismic experiment for the interpretation of subsurface layers and their discontinuities. The primary reflections in the raw seismic data are always hindered by the wave fields arising from several unwanted sources such as: diffractions, ground roll, airwave etc. and unknown random signals. Separation of signal from the noise is an important task in geophysical signal processing industry. The accuracy of seismic data interpretation mainly depends on the quality of the data i.e., Signal-to-Noise Ratio (S/N). Therefore, separation of unwanted signals from the seismic field data is almost essential and a challenging task in seismic industry for accurate and geologically consistent physical interpretation of primary reflections for understanding the study area. In the following section, we begin with the basic classification of different kinds of noises based on their statistical and spectral characteristics before proceeding to discuss about denoising techniques used in seismic industry.

1.2 General Classification of Noise in Seismic Data

As discussed above, it is not possible to discern all the sources of noise in the seismic data to discuss their characteristics completely. 'What is noise?' is highly subjective (Scales and Snieder 1998). Simple visual inspection of the data cannot assure

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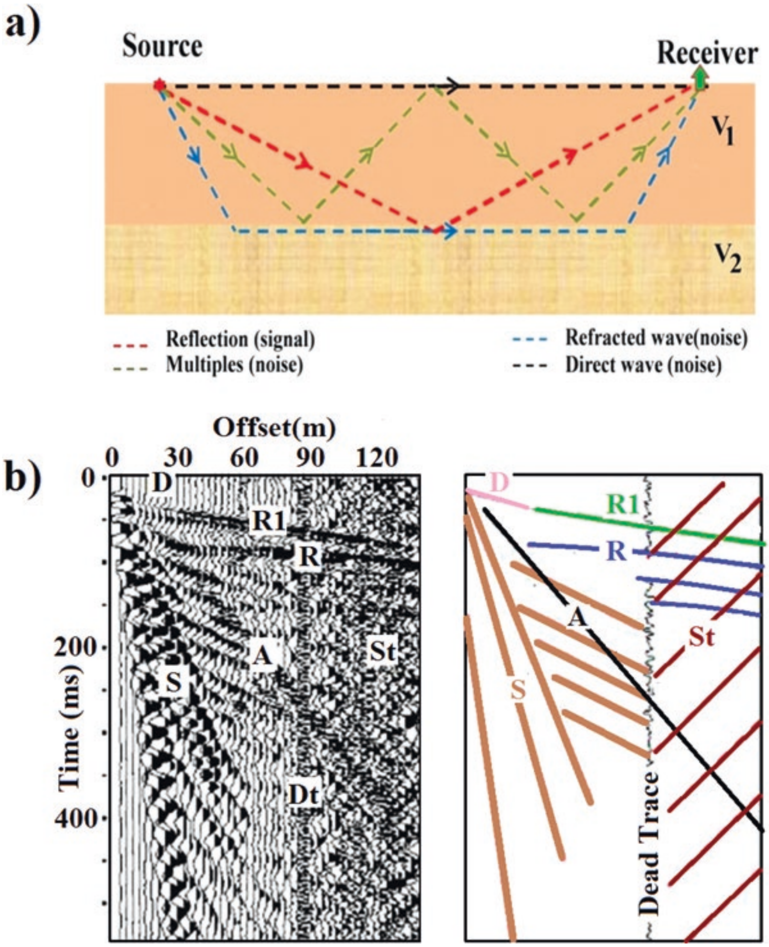

Fig. 1.1 (**a**) Schematic illustration of different types of waves in seismic reflection experiment. (**b**) Different kinds of seismic wave fields in the shot gather. (*A* Airwave, *D* Direct wave, *R* Reflected wave, *R1* Refracted wave, *S* Surface wave, *St* Surface wave (traffic), *Dt* Dead channel)

the identification of noise and its nature. However, based on the information and literature available today, depending on the statistical characteristics, the noises that corrupt the seismic data are broadly categorized into two types, namely (i) random/incoherent and (ii) coherent noises (Telford and Sheriff 2010).

1.2.1 Random Noise

The disturbances in the seismic signal amplitudes that lack the trace-to-trace spatial coherency are considered as the random noise. The random/white noise does not result from the sources that generate the seismic energy. Near-surface scattering, wind and rain are some examples of possible sources of random noises in land seismic reflection data. The white noise occupies all the frequencies with the same spectral power results with constant shift in the spectral power at all frequencies. Therefore, constant scaling (i.e., dividing the spectral power of each frequency component in the data by constant number) will help reducing the random noise. In general, these random noise sources are non-stationary, i.e., they do not add to the original reflections in the same manner, if we acquire data at two different times (4D manner).

1.2.2 Coherent Noise

The seismic source is the origin of some spatially distributed coherent noises. It is an undesirable additive energy to the primary reflections. Such energy shows consistent phase from trace to trace. The multiple reflections/multiples, surface waves like ground roll and airwaves, coherent scattered waves, dynamite ghosts etc., are the coherent noises that are commonly present with the seismic data (Fig. 1.1b). Improper removal of coherent noise affects nearly all the subsequent data processing and complicates the interpretation of geological structures. The land seismic reflection data mainly contains ground roll and it is obvious to know its characteristics for appropriate removal. The ground roll is the low velocity (<1000 m/s), low frequency (<15 Hz) and high amplitude surface/Rayleigh wave energy that travel along the surface. Because of the dispersion, different frequency components produce different ground roll mode in the data. In addition, the coloured noise is also well known in seismic signal processing, which is a sub-branch of coherent noise. The noise that occupies characteristic frequency spectrum is known as coloured noise.

The primary seismic events show trace-to-trace correlation and their energy is limited to specific frequency band. In general, the signal of interest is defined as the energy that shows trace-to-trace coherency. But, as discussed above, the coherent noise also shows spatial trace-to-trace coherency. Thus the spatially coherent noise is the most troublesome and deceptive compared to random noise as it shows consistent trace-to-trace correlation (Telford and Sheriff 2010) and sometimes occupies the frequency band of signal. Although the frequency analysis (Claerbout 1976; Yilmaz 2001) is useful to identify the band limited seismic reflection signals, the analysis fails to identify the deceptive coherent or coloured noises having frequency within the spectral band of the primary signal. The statistical techniques provide the estimates of the data like standard deviation, variance etc., which enable us to identify the noise up to certain extent. Geologically consistent seismic interpretation requires the seismic sections without noise and artefacts. Hence, it is obvious to suppress the noise using appropriate techniques in the initial processing stages.