ADVANCED DIGITAL SIGNAL PROCESSING OF SEISMIC DATA

Seismic data must be interpreted using digital signal processing techniques in order to create accurate representations of petroleum reservoirs and the interior structure of the Earth. This book provides an advanced overview of digital signal processing (DSP) and its applications to exploration seismology using real world examples. The book begins by introducing seismic theory, describing how to identify seismic events in terms of signals and noise, and how to convert seismic data into the language of DSP. Deterministic DSP is then covered, together with non-conventional sampling techniques. The final part covers statistical seismic signal processing via Wiener optimum filtering, deconvolution, linear-prediction filtering, and seismic wavelet processing. With over 60 end-of-chapter exercises, seismic data sets, and data processing MATLAB codes included, this is an ideal resource for electrical engineering students unfamiliar with seismic data, and for earth scientists and petroleum professionals interested in DSP techniques.

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To my dear parents and family.

To KFUPM and my great country.

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Preface

It is well known that Digital Signal Processing (DSP) plays an important role in many applications of science and engineering disciplines, including seismology, sonar, radar, medical, and communications. In the case of seismology, the application of signal processing theory began with the work of the Geophysical Analysis Group at the Massachusetts Institute of Technology (MIT) between 1960 and 1965, where it was one of the great historical milestones in seismic data processing.

Interestingly, oil and gas are still considered to be extremely important natural resources for human beings, with many beneficial applications. Such precious resources are buried in deep land or marine subsurface geological structures. In order to produce oil, we need first to estimate as accurate as possible an image of the subsurface. This can be done by listening to the echo caused by artificial earthquakes via a surveying method known as seismic exploration. The process generally requires acquisition, processing, and interpretation of seismic data, where DSP plays an important role in estimating seismic subsurface images.

It is known that the energy industry already faces critical shortages across the entire spectrum of skilled positions and our future needs will only grow. This requires education and training of tens of thousands of new scientists and engineers, in addition to geologists, geophysicists, and other vital workers. This is all the more important given the low number of students joining geosciences-related disciplines. Therefore, with the increased demand for oil and gas production, seismic data acquisition, processing, and interpretation will require more manpower and innovative thinking. Part of this innovation will rely on advancing seismic signal analysis and processing techniques and algorithms. And this book, in essence, discusses deterministic and statistical DSP theories but with various examples based on seismic exploration data. It provides a blended mix between the theoretical as well as the practical aspects of DSP and its application to the processing of seismic data.

For electrical engineers, particularly those in the area of DSP, the book provides the seismic surveying theory background that is necessary for understanding seismic data and, hence, for preparing them to properly process seismic data in academia or industry. It also covers deterministic and statistical DSP theory, with a focus on practical DSP for seismic data processing in a language that electrical engineers will understand. The book also serves as an important reference for geosciences researchers and professionals, who are interested in digging deeper into the theory of DSP and achieving a more precise and in-depth understanding of their applications to seismic data, which enables them to develop advanced seismic data processing algorithms with a DSP center. The main book features are as follows:

- Suggested senior level undergraduate and graduate Electrical Engineering course syllabi.
- Sufficient examples, illustrations, and figures for each chapter as applicable.
- Exercises, at the end of each chapter, including computer assignments for various topics using MATLAB.
- Synthetic and real seismic data short gathers for illustration figures, and computer assignments.

Chapter 1 is an introduction with the main aim of motivating readers regarding the subject of seismic signal processing. It also focuses on general seismic data acquisition, processing workflow, the seismic convolution model, and seismic interpretation. On the other hand, Chapter 2 mainly gives an intensive overview of the fundamentals and physical principles on which seismic methods are based. It provides the geophysical background that is necessary for understanding seismic data and, hence, the reader will obtain a clearer understanding of how to properly process the data in order to ultimately obtain better seismic images that are used for accurate interpretation.

Signal analysis in the spectral or other domains is very important and assists in obtaining a better understanding of signals. When dealing with seismic data sets, it becomes almost standard to analyze them in the 2-D frequency-wavenumber domain. Also, other discrete transforms are very useful for processing seismic data sets such as the Radon transform, which can be used for seismic wavefield decomposition as well as seismic multiple removal. Of course, this would also require a brief review of the z-transform and the various usages in seismic applications. Hence, in Chapter 3, spectral analysis of seismic data and useful transforms are discussed.

Chapter 4 presents sampling theory for seismic data, where whenever we talk generally about digital data and their acquisition systems, we must explain Shannon sampling theory for sampling continuous time (space) signals. Also, the chapter explains the aliasing effects due to under-sampling of seismic data sets. This, of

course, includes some discussion of how to choose the best parameters for sampling seismic data given the opportunity to do so. Moreover, the theory of compressive sensing (CS) is currently considered the state of the art theory of DSP, with many applications related to signal and image compression, signal recovery, and many other applications. CS is currently used for various seismic data processing problems. Hence, in this chapter we introduce CS principles and provide a few seismic data processing-related applications.

Seismic applications of digital filtering theory are presented in Chapter 5. 1-D FIR and/or IIR digital filters, such as low-pass or band-pass, are used heavily to enhance the signal-to-noise (SNR) ratio of acquired seismic data. Furthermore, 2-D digital filters such as fan filters have become standard in removal of surface waves accompanying seismic data records. Solving the wave equation numerically may also require using FIR or IIR digital filters such as explicit depth wavefield extrapolation filters.

When using low-pass or band-pass filters to attenuate unwanted seismic energy from seismic data records, so-called seismic vertical resolution will be affected, i.e., the high frequency components of seismic waves are attenuated and some processes such as deconvolution must, therefore, be used. Also, multiple or ghost noise types can be greatly attenuated when using predication error filters. Seismic wavelets and wavelet processing are essential to understand, since wavelets are a main component of the seismic convolution model. All of these filters are various applications of Wiener optimum filtering processes. Hence, in Chapters 6–8 we provide the fundamentals of optimum filtering and show different applications of this important theory in seismic data processing.

I would like to take this opportunity to thank my protégé H.E. Professor Khaled S. Al-Sultan, Previous Rector, King Fahd University of Petroleum & Minerals (KFUPM), and the university for their support. I would also like to thank the Electrical Engineering Department, KFUPM, and its chairman, Dr. Ali A. Al-Shaikhi, for the opportunity to teach, over the last 10 years, many special topics courses around the book subject, which greatly helped to shape the book's content and exercises. I cannot forget my dear colleague, Professor Abdullatif A. Al-Shuhail, Earth Sciences Department, who has been my research partner since 2008, and has supported me in the course and its seismic theory background over the last 10 years. Without his assistance, neither the book nor the course would exist. Special thanks are due to my colleagues from Saudi Aramco, including Dr. Saleh Al-Dossary, for being welcoming and supportive on my visits with students to their Seismic Data Processing facilities for allowing me access. Also, I sincerely thank Professor Stewart Greenhalgh, Saudi Aramco Chair Professor, Geosciences Department, College of Petroleum Engineering & Geosciences, KFUPM, for taking the time to review the book. I thank also Dr. Arbab Latif, Mr. Abdullah F. Al-Battal,

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