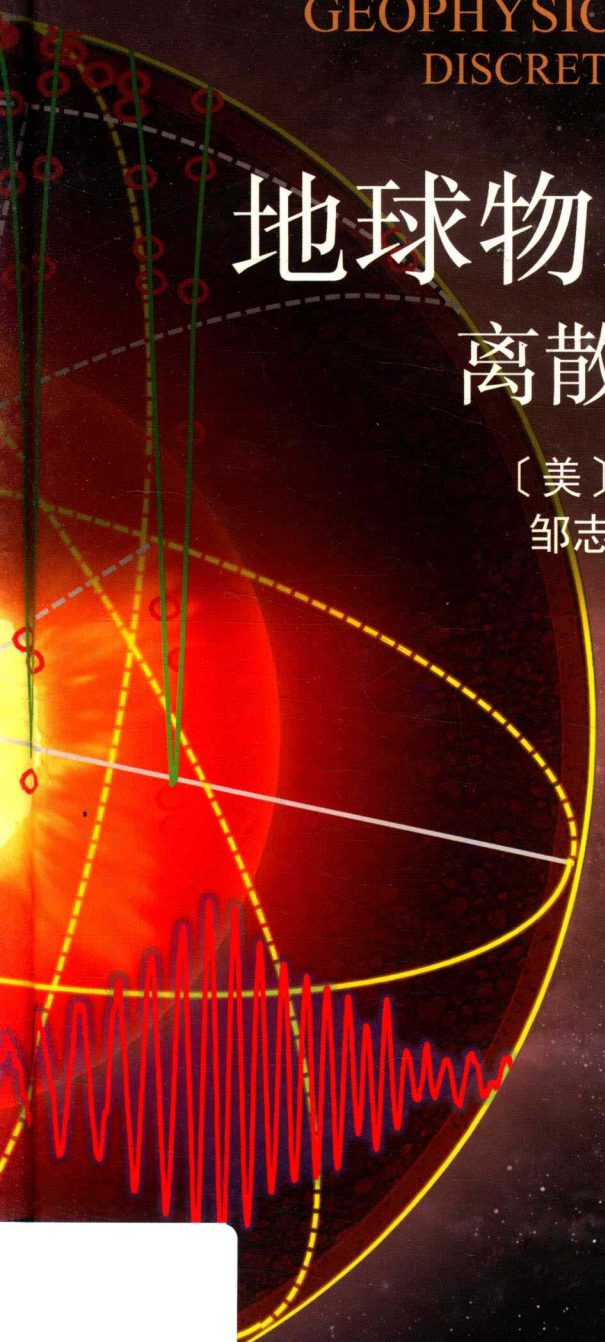
海底科学与技术丛书

GEOPHYSICAL DATA ANALYSIS
DISCRETE INVERSE THEORY

地球物理数据分析
离散反演理论

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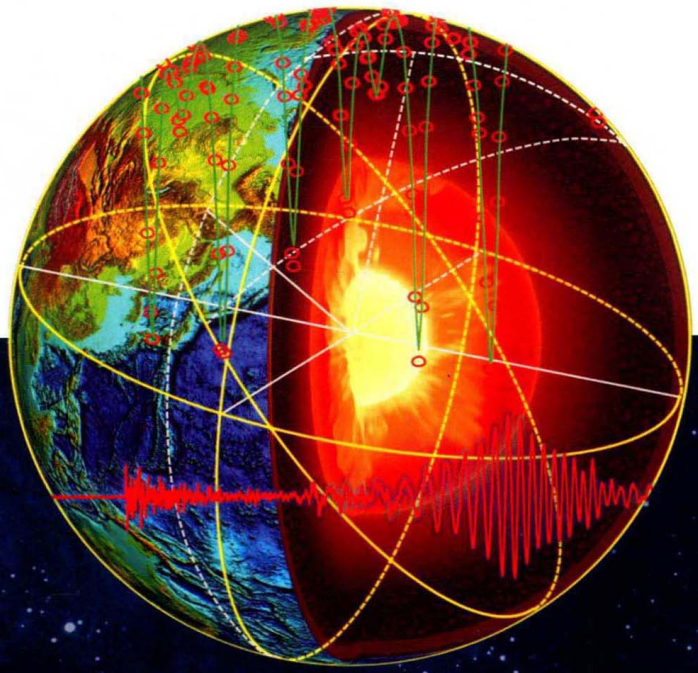
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内 容 简 介

地球物理反演是处理复杂地球物理问题的重要手段,它基于观测数据,利用数学手段来估计地球物理参数的分布状态、时空演化。近年来,地球物理反演被广泛应用于板块构造、资源能源勘探、环境变化分析、气象预测、海洋水体监测、行星构造等研究领域,是地球物理学、环境科学、大气科学、物理海洋学、遥感学等学科的重要手段。本书以离散反演理论为对象,在介绍离散反演理论所需要的编程和基本数学工具的基础上,系统讲解线性反演理论的三种观点,并介绍非线性反演理论、因子分析和连续反演理论的思想和要点,讨论地球物理的典型反问题,列举离散反演理论在地球物理中的应用实例。随书附带的网站提供诸如例题源代码在内的学习支撑材料,可供读者自行练习,以理解相关章节的内容。

本书既可用作地球物理学、地质资源与地质工程、海洋科学等相关专业的高年级本科生和研究生教材,也可作为从事地球物理、地球化学、物理海洋、大气、数学地质、遥感、测绘等工作的科研人员的参考用书。

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注意

本书涉及领域的知识和实践标准在不断变化。新的研究和经验拓展我们的理解,因此须对研究方法、专业实践或医疗方法作出调整。从业者和研究人员必须始终依靠自身经验和知识来评估和使用本书中提到的所有信息、方法、化合物或本书中描述的实验。在使用这些信息或方法时,他们应注意自身和他人的安全,包括注意他们负有专业责任的当事人的安全。在法律允许的最大范围内,爱思唯尔、译文的原文作者、原文编辑及原文内容提供者均不对因产品责任、疏忽或其他人身或财产伤害及/或损失承担责任,亦不对由于使用或操作文中提到的方法、产品、说明或思想而导致的人身或财产伤害及/或损失承担责任。

Preface to the Chinese Edition

I wrote the first draft of Geophysical Data Analysis: Discrete Inverse Theory during six weeks of activity in the summer of 1983 that was so intense that my wife began to refer to herself as a *Book Widow*. I was very excited about the material, for I had the sense that Inverse Theory would become increasingly important in the coming decades-an intuition that proved correct! I was a twenty-nine years old Assistant Professor in the College of Oceanography at Oregon State University. Inverse Theory was one of my teaching assignments. I had at that juncture taught it only twice, both times to tiny classes of five or six graduate students. I developed the lecture material-and the students solved their homework problems-on the university's new Prime 750 mini-computer, which seemed powerful at the time but had about 0.1% of the computing capacity of the cell phone in my pocket today. At the same time, I was writing-up two research projects that explored applications of Inverse Theory, one on cross-borehole tomography (Menke,1984a), and the other on sieve analysis (Menke,1984b). The former attracted considerable attention among exploration seismologists; the latter was ignored by sedimentologists.

That was thirty-six years ago.

Subsequently, Geophysical Data Analysis: Discrete Inverse Theory has become very well-regarded among researchers and students, alike. I am proud to say that it has been cited more than four thousand times in the peer-reviewed literature and that it has been translated from its original English into several other major languages-including now Chinese. Several times I have worked to revise the book, adding newly-learned material while doing my best to preserve the overall approach of the original. The Third Edition represents a major effort on my part, for it adds tutorials, case studies and problem sets written in the *MatLab* ® data manipulation language, and provides fully-functional code through a companion website. It goes a long way to implement my dream that that students be able to solve realistic, computer-based inverse theory problems without needing years of training in computation. The incorporation of Adjoint Methods, which are having ever-

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growing influence on the way Inverse Theory problems are formulated, also was a challenge, because they require mathematical concepts more advanced than the differential calculus and linear algebra that were the design-level of previous editions. My approach is to emphasize the similarity between concepts needed to understand Adjoint Methods and those introduced earlier in the book.

The field of Inverse Theory has flourished in the last thirty-six years. Many new methods have been developed and many new discoveries have been made about the Earth through its application to new data sets. I am therefore rather surprised that many of the core ideas that I set out to communicate in the original version are as true and important today as they were in 1983.

The first idea is that the fundamental principles of Inverse Theory are few, easy to learn and widely-applicable. The most important principle is that much of our knowledge of the Earth is obtained through fitting models to data. Although the fitting process can be accomplished in a variety of ways, the least-squares principle, in which the square of the misfit is minimized, stands out as being the most useful. Almost as important is the notion that all observations contain error and that the process of fitting models to data transfers that error from the observation to the model parameters. The results are useful when error is suppressed and nonsensical when it is amplified. Critically important is being able to identify these two cases. A last principle that is especially important in geophysical applications relates to the wide range of scale-lengths in the Earth -microscopic to global. An experiment that is well-suited for detecting features at one scale may be completely insensitive to others. Thus, the ability to quantify resolving power is a critical aspect of experimental design.

The second idea is that developing the facility to critically examine data is essential for uncovering relationships among them and for avoiding blunders. The essential paradigm of Inverse Theory is the fitting of a model to data. The success of that paradigm can only be assessed by evaluating the quality of the fit. Inverse Theory provides several summary indicators, such as the root-mean-squared error, that allow the degree of success to be quantified. But these indicators are only the starting point. A more thorough examination provides insight into which data are most-poorly fit. It might point to a specific part of the dataset being unreliable (such as time periods in which a sensor is malfunctioning) or having a more complicated behavior than the model can accommodate (such as oscillating when a certain parameter is large). The second reason is especially important, because it can move the research towards the development of a better model. Examining one's data is

especially challenging for problems with very large datasets. Fortunately, Inverse Theory simplifies the development of intermediate data products that can facilitate the analysis. Any student or researcher who can simply look at her or his data and understand its main features has developed a very powerful intellectual tool!

Finally, the third idea is that a person's understanding of Inverse Theory is best developed through a process that combines the learning of new techniques (say by reading a chapter in this book) with applying them to realistic problems (say by working through the problem sets and case studies). In some ways, this process is easier today than in the 1980's, because widely-available software products, such as the *MatLab* ® environment, have standardized many operations (such as computing a matrix inverse or plotting a timeseries) that where once extremely idiosyncratic. Nevertheless, learning to effectively use a computer, and dealing with numerical computations, are still very much part of the process of performing Inverse Theory. Fortunately, most of the students I encounter are very excited about doing just that!

The speed and memory of computers have increased vastly since the 1980's. Back then, a problem with 10^4 model parameters was considered very challenging; today the same might be said of a problem with 10^8 of them. However, the improvement in computing capacity, in and of itself, has had little effect on the practice of Inverse Theory. It merely has allowed it to be applied to larger and larger datasets. More fundamental was a theoretical advance called the Adjoint Method (discussed in the latter chapters of this book). It allows a key inverse theory quantity to be calculated for hitherto fore intractable models-those involving the numerical solution of differential equations, such as simulations of atmospheric circulation and of seismic wave propagation in the solid earth. Although developed by Hall et al. (1983) around the time I was writing the first draft of this book, adjoint methods could not be exploited fully until computer capacity grew to the point where useful simulations routinely could be made. While adjoint methods are now a standard part of Inverse Theory, their application requires substantial familiarity with the inner workings of numerical simulations. Consequently, collaborative efforts of teams of students and researchers with widely-varying expertise are becoming increasingly important.

The final results of an Inverse Theory analysis often include visually-compelling images, and these have led to very substantial advances in scientific knowledge. This is especially true in geophysics, where geotomographic images have played a major role in elucidating the Earth's internal structure. Nevertheless, although the fidelity of geotomographic images have improved over the years, the improvement has not kept pace with their counterparts

in other fields, and especially medical imaging (e.g. Singh and Sheik, 2017) and engineering (e.g. Menke et al., 2018). I point out this disparity to not to criticize my own work or the work of my colleagues, but to challenge the readers of this book, and especially the student among them. Cleverer experimental designs, more accurate instrumentation, denser measurements, and more realistic models all are needed. There is exciting work for you to do!

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Palisades New York
May 1, 2019

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中文版序

1983 年夏天，我花费了六周的时间写成了《地球物理数据分析：离散反演理论》的初稿，写这本书的时间非常紧凑，以至于我的妻子将自己称为“书寡妇”。这本书让我感到非常兴奋，因为我感觉反演理论在未来几十年将变得越来越重要——这种直觉被证明是正确的！我当时 29 岁，是俄勒冈州立大学海洋学院的助理教授，反演理论是我的教学任务之一。在那时，我只教授了两次，且两次教授的都是 5 ~ 6 个研究生的小班。我编写了课程材料，学生在学校新推出的 Prime750 小型计算机上解决了他们的作业问题，这台计算机在当时看起来功能似乎很强大，但它的运算能力只有目前手机的 0.1% 左右。与此同时，我那时刚写完两个探索反演理论应用的研究项目申请书，一个关于井间层析（Menke，1984a），另一个关于筛分分析（Menke，1984b）。前者引起了勘探地震学家的极大关注，而后者却被沉积学家忽视。

那是 36 年前的事了。

《地球物理数据分析：离散反演理论》出版后，在研究人员和学生中都得到了认可。我自豪地说，它在同行评审的文献中被引用了 4000 多次，并且已经从原来的英语版翻译成其他几种主要的语言版——包括现在的中文版。我曾多次修改这本书，在尽最大努力保持原著整体风格的同时添加新的学习材料。第三版代表了我的一项主要工作，因为它添加了用 *MatLab* ®数据操作语言编写的教程、案例研究和问题集，并通过配套网站提供了完整的功能代码。这距离实现我的梦想还有很长的路要走，即让学生在不需要多年计算机训练的情况下，能够解决现实基于计算机的反演理论问题。伴随法对反演理论问题的形成方式产生了越来越大的影响。伴随法的引入也是一个挑战，因为它们需要的数学概念比先前版本所用的微积分和线性代数设计水平更先进。我采用的手段是强调理解伴随法所需的概念与本书介绍的传统概念之间的相似性。反演理论在过去的 36 年里蓬勃发展。目前已经建立了许多新的方法，并且通过将其应用于新数据集，使我们对地球有了很多新的发现。且令我感到非常惊讶的是，1983 年我在原始版本中提出的许多核心思想，在今天同样真实且重要。

第一种思想是，反演理论的基本原理少，易学且适用范围广。最重要的原则是，我们对地球的大部分了解都是通过模型与数据的拟合获得的。虽然拟合数据的过程

可以通过多种方法来完成,但最小二乘原理(即最小化残差的平方)是其中最有用的方法。同样重要的是,所有的观测都包含误差,模型拟合数据的过程会把误差从观测值传递到模型参数。当误差缩小时,结果是有意义的;当误差放大时,结果则是无意义的。因而,能够识别误差被缩小还是放大这两种情况至关重要。在地球物理应用中,特别重要的最后一个原则与地球上从微观到全球的各种尺度有关。在某一尺度特别适合用来检测特征的实验可能对其他尺度的特征完全不敏感。因此,量化分辨力的能力是实验设计的一个关键方面。

第二种思想是,开发一种能够严格审查数据的工具,这对于揭示数据之间的关系以及避免错误至关重要。反演理论的基本模式是模型与数据之间的拟合。这种模式的成功与否只能通过评估拟合的质量来衡量。反演理论提供了几个总体指标,如均方根误差,它可以量化拟合逼近的程度。但这些指标只是起点,更彻底的检查是深入了解哪些数据拟合最差。它可能会指出数据集的特定部分不可靠(如传感器发生故障的时间段),或具有模型无法适应的更复杂的行为(如当某个参数很大时发生的振荡)。后一个作用尤其重要,因为它可以推动研究朝着建立更好模式的方向发展。对于非常大的数据集,审查数据尤其具有挑战性。幸运的是,反演理论使中间数据的产生变得简单,这有助于进行分析。任何学生或者研究人员,只要能够查看他/她的数据并了解其主要特征,就可以开发出非常强大的智能工具!

第三种思想是,一个人加深对反演理论的理解是一个渐进的过程,即把学习到的新技术(如阅读本书的第 1 章)与实际问题的应用(如通过问题求解和案例研究来进行应用)逐渐相结合。在某些方面,这个过程现在实现起来比 20 世纪 80 年代更容易,因为广泛使用的软件(如 *MatLab* ®环境)已经使许多操作(如计算矩阵逆或者绘制时间序列)标准化,而这些操作曾经不为人所熟知。尽管如此,学习有效地使用计算机和处理数值计算仍然是进行反演过程中非常重要的一部分。幸运的是,我遇到的大多数学生或者研究人员都对这样做非常兴奋!

自 20 世纪 80 年代以来,计算机的运算速度和存储能力得到大大提升。那时,求解含有 10^4 个模型参数的问题被认为是非常具有挑战性的,而今天,可能会认为求解 10^8 个模型参数是非常具有挑战性的。然而,运算能力的提高对反演理论的实践影响不大。它只是允许将反演理论应用于越来越大的数据集。更根本的是一种称为伴随法的理论进步(在本书的后面几章中讨论)。对于那些迄今难以处理、涉及微分方程数值解的模型(如对大气环流和固体地球中的地震波传播的模拟),伴随法能够对一个关键反演理论量进行计算。尽管在我第一次写这本书初稿的时候,Hall 等(1983)已提出了伴随法,但该方法在计算机运算能力提升到可以常规地进行有用模拟之前,难以得到充分研究。虽然伴随法现在是反演理论的一个标准部分,但应用该方法的过程要求人们掌握数值模拟的内在机制。因此,具有不同专业广泛知识的学生和研

究人员之间的团队协作变得越来越重要。

反演理论分析的最终结果通常含有视觉上引人注目的图像，这是科学知识的巨大进步。地球物理学尤其如此，如地球层析图像在解释地球内部结构方面发挥了重要作用。然而，尽管近年来地球层析图像的准确度有所提高，但其改进并没有与其他领域的同行保持同步，尤其是医学成像（Singh and Sheik，2017）和工程领域（Menke et al.，2018）。我认为这种差异并不是批评我自己或我的同事的工作，而是挑战这本书的读者，尤其是学生。我们需要更聪明的实验设计，更精准的仪器，更密集的测量以及更真实的模型。有很多令人兴奋的工作值得你们去尝试！

William Menke
哥伦比亚大学拉蒙特-多尔蒂地球观测站
纽约帕利塞兹
2019年5月1日

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Foreword to the Chinese Edition

Geophysical Data Analysis: Discrete Inverse Theory is an excellent textbook on the topic of geophysical inverse, and has been adopted by classes in many universities around the world. This book was also used as reference and cited by many new books in the field of geophysical inverse theory. There were three editions of this book, which were published in 1984, 1989, and 2012, respectively. The published time of the three versions corresponded to the formulation, quick development, and completement stages of the geophysical inverse theory. This book is the Chinese translated version of the third edition, which covers the basic theory and new progress of the geophysical inverse. The third edition combines the MatLab programming with the geophysical inverse method, and introduces them with practical examples, which would be helpful for readers to better understand the related theories and algorithms.

Geophysical inverse is the core of geophysical studies. It is built on the basis of the mathematical relations between data and model parameters given by geophysical theory (or model), and aims to estimate the best model parameters through minimizing the error between predicted data and observed data and solving the mathematical optimization problems. The geophysical inverse theory is the efficient way of studying important scientific problems, such as climate change, structure and motion of marine water, internal structure of the Earth, mechanisms of great earthquakes, distribution of energy and resources etc., supports the important field of national safety and frontiers of scientific research, such as prediction of geohazards, exploitation of energy and resources, exploration of planets etc., and has made significant achievement.

The purpose of translating this book is to provide a textbook for a course of Geophysical Inverse, which is designed for junior students majored in Exploration Technology and Engineering in Ocean University of China. Current textbooks of geophysical inverse are mainly designed for graduate students. Those books either involve many mathematical contents that are not familiar for undergraduate students, or have too many contents to be

completely taught in one semester. This book is suitable for teaching a one – semester undergraduate course in China for its appropriate length and hardness. The programming exercises and examples in the book fit the current situation of increasing the practical application capabilities of Chinese students. By combining with the original English edition, teaching this book is helpful for bilingual education in Chinese universities, which might increase the theoretical level, capability of practical application, and international vision of students majoring in geophysics and related subjects.

The book was translated byZhihui Zou, and was proofread and revised by Jianzhong Zhang. Zhihui Zou unified the draft of whole book. We thank Miss. Lingzhi Kong for her translating parts of preface, exercises, and index. We want to thank Mr. Wenliang Sun, Mingliang Han, Rui Ma, Fujian Gao, Wenbin Yu, and Longlong Song for their contributions in revising the draft, which ensure the finish of the book on time. The authors want to thank their family members for their continuous supports and encouragement, which make the finish of this book be possible. We thank Dr. Zhijun Du for his constructive suggestions during translating the book, and thank Dr. William Menke, the author of the English version of the book, for writing the preface for the translated Chinese version. The publishing of this book was supported by Key Lab of Submarine Geosciences and Prospecting Techniques, Ministry of Education, and National Key R&D Program of China (Artificial Intelligence Based Research and Development of Joint Inversion of Gravity, Magnetic, Electric and seismic data, 2018YFC0603604).

Due to the limitation of our knowledge, there must be mistakes and errors in the book. We hope that the readers can send us their comments and corrections to improve the book.

Zhihui Zou, Jianzhong Zhang

2019.7.13

译 者 序

《地球物理数据分析:离散反演理论》是国外优秀的地球物理反演教材,已被国际上多所大学广泛采用,并被大多数新编的地球物理反演方面的教材参考和引用。本书原著有三个版本,分别出版于 1984 年、1989 年和 2012 年。这三个时间节点对应于地球物理反演理论形成、快速发展和完善的重要阶段。本书是第三版的中文译本,该版既有地球物理反演的基础知识,也涵盖了最新的理论进展,并将当前广泛使用的 *MatLab* 编程与反演方法相结合,配合大量实例,便于读者对相关知识和算法的深入理解。

地球物理反演是地球物理学的核心研究内容,它基于地球物理理论(或模型)设定数据与模型参数之间的数学关系,借助数学的最优化问题解法,最小化预测数据与观测数据之间的差值,达到估计最佳模型参数的目的。地球物理反演是研究气候变化、海洋水体结构和运移、地球内部结构、大地震发震机制、资源能源的分布等重要科学问题的有效途径,支持着地质灾害预防、资源能源开发、行星探索等重要的国计民生和学术前沿领域,近年来取得了显著的成就。

翻译本书的初衷是为中国海洋大学勘查技术与工程专业高年级本科生开设的《地球物理反演》课程匹配教材。国内外现有的地球物理反演教材大多针对研究生,内容涉及的数学知识超出了本科生的学习范围,或者篇幅较长,难以在一个学期内学完。本书在篇幅和难易程度方面均适应当前国内的教学情况,其中的编程习题和例题也适应提高本科生实际应用能力的教学新形势。将本书配合英文原著,有助于高校开展双语教学,提高地球物理相关专业学生的理论水平、动手能力,开拓国际化视野。

本书由邹志辉翻译完成,张建中对译稿进行了审校和修改,最后由邹志辉统稿。感谢孔玲芝协助翻译和审校了引言、课后习题和索引的部分内容。孙文亮、韩明亮、马锐、高福建、余文斌、宋龙龙等在翻译过程中也帮助校对了文字,他们的努力工作保证了本书的顺利完成,在此致以衷心的感谢;同时要感谢家人对我们工作一如既往的支持,这是本书能够成稿的保障;感谢杜志俊教授在翻译本书过程中提出的建设性意见;感谢原著者 William Menke 教授特意为本书中文版写前言。本书得到了海底科学

与探测技术教育部重点实验室的大力支持和资助，并获得了国家重点研发计划项目“基于人工智能技术的重磁电震联合反演技术研发”（2018YFC0603604）的资助，在此表示感谢。

由于本书译者水平有限，不足之处在所难免，希望广大读者批评指正。

邹志辉　张建中

2019 年 7 月 13 日

Preface

For now we see through a glass, darkly, but then...

Paul of Tarsus

Every researcher in the applied sciences who has analyzed data has practiced inverse theory. Inverse theory is simply the set of methods used to extract useful inferences about the world from physical measurements. The fitting of a straight line to data involves a simple application of inverse theory. Tomography, popularized by the physician's CT and MRI scanners, uses it on a more sophisticated level.

The study of inverse theory, however, is more than the cataloging of methods of data analysis. It is an attempt to organize these techniques, to bring out their underlying similarities and pin down their differences, and to deal with the fundamental question of the limits of information that can be gleaned from any given data set.

Physical properties fall into two general classes: those that can be described by discrete parameters (e.g., the mass of the earth or the position of the atoms in a protein molecule) and those that must be described by continuous functions (e.g., temperature over the face of the earth or electric field intensity in a capacitor). Inverse theory employs different mathematical techniques for these two classes of parameters: the theory of matrix equations for discrete parameters and the theory of integral equations for continuous functions.

Being introductory in nature, this book deals mainly with "discrete inverse theory," that is, the part of the theory concerned with parameters that either are truly discrete or can be adequately approximated as discrete. By adhering to these limitations, inverse theory can be presented on a level that is accessible to most first-year graduate students and many college seniors in the applied sciences. The only mathematics that is presumed is a working knowledge of the calculus and linear algebra and some familiarity with general concepts from probability theory and statistics.

Nevertheless, the treatment in this book is in no sense simplified. Realistic examples,

drawn from the scientific literature, are used to illustrate the various techniques. Since in practice the solutions to most inverse problems require substantial computational effort, attention is given to how realistic problems can be solved.

The treatment of inverse theory in this book is divided into four parts. Chapters 1 and 2 provide a general background, explaining what inverse problems are and what constitutes their solution as well as reviewing some of the basic concepts from linear algebra and probability theory that will be applied throughout the text. Chapters 3-7 discuss the solution of the canonical inverse problem: the linear problem with Gaussian statistics. This is the best understood of all inverse problems, and it is here that the fundamental notions of uncertainty, uniqueness, and resolution can be most clearly developed. Chapters 8-11 extend the discussion to problems that are non-Gaussian, non-linear, and continuous. Chapters 12-13 provide examples of the use of inverse theory and a discussion of the steps that must be taken to solve inverse problems on a computer.

MatLab scripts are used throughout the book as a means of communicating how the formulas of inverse theory can be used in computer-based data processing scenarios. *MatLab* is a commercial software product of The *MathWorks*, *Inc.* and is widely used in university settings as an environment for scientific computing. All of the book's examples, its recommended homework problems, and the case studies of Chapter 12 use *MatLab* extensively. Further, all the *MatLab* scripts used in the book are made available to readers through the book's Web site. The book is self-contained; it can be read straight through, and profitably, even by someone with no access to *MatLab*. But it is meant to be used in a setting where students are actively using *MatLab* both as an aid to studying (that is, by reproducing the examples and case studies described in the book) and as a tool for completing the recommended homework problems.

Many people helped me write this book. I am very grateful to my students at Columbia University and at Oregon State University for the helpful comments they gave me during the courses I have taught on inverse theory. Mike West, of the Alaska Volcano Observatory, did much to inspire this revision of the book, by inviting me to teach a mini-course on the subject in the fall of 2009. The use of *MatLab* in this book parallels the usage in *Environmental Data Analysis with MatLab* (Menke and Menke, 2011), a data analysis textbook that I wrote with my son Joshua Menke in 2011. The many hours we spent working together on its tutorials taught us both a tremendous amount about how to use that software in a pedagogical setting. Finally, I thank the many hundreds of scientists and mathematicians whose ideas I drew upon in writing this book.

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