国防电子信息技术丛书

Polarisation: Applications in Remote Sensing

极化建模与雷达遥感应用

（英文版. 中文评注）

［英］ Shane R. Cloude 著

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内 容 简 介

作者从电磁波的物理特性入手，深入浅出地阐述了极化和极化干涉技术基本概念中所蕴涵的物理意义以及贯穿其中的核心思想，使读者易于理解极化和极化干涉技术的本质和基本特性。本书首次将波极化与雷达干涉的主题结合在一起，重点论述两者融合后的极化干涉技术的重要发展。本书共9章，分别是极化电磁波、去极化与散射熵、表面散射与体散射去极化、分解理论、雷达干涉技术概述、极化干涉理论、表面散射与体散射相干性、运用极化干涉进行参数估计，以及极化干涉技术应用。

本书适合作为微波电磁场及其应用，特别是雷达遥感领域研究生两个学期的教学用书，也可以作为遥感领域中科研人员和工程师的参考书。物理光学，特别是极化与光散射方面，以及应用数学方面的研究人员也能从本书中得到启发。

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导读

经过 60 余年的发展，合成雷达技术正朝着高分辨、多极化、多波段及其定量化应用不断发展，其中极化雷达遥感技术正是当前研究的热点。近年来发射和计划发射的星载合成孔径雷达都具有极化能力。从第一代（日本 JAXA 的 ALOS-1，加拿大 CSA/MDA 的 Radarsat-2，以及德国 DLR/Astrium 的 TerraSAR-X）逐渐发展更新到第二代（日本 JAXA 的 ALOS-2，加拿大 CSA/MDA 的 RCM，德国 DLR/Astrium 的 Tendem-L，以及欧洲 ESA 的 Sentinel1 和 BIOMASS），极化和极化干涉技术获得了前所未有的关注和投入。因此，迫切需要关于极化和极化干涉雷达技术基本原理和应用实例的教科书。

Polarisation: Applications in Remote Sensing 一书由国际著名极化雷达干涉专家 Shane R. Cloude 撰写。Shane R. Cloude 教授是极化分解理论以及极化相干层析等技术的提出者，对极化和极化干涉理论有着系统深入的理解。本书是基于作者 20 余年的相关研究经验，以及与那些在此领域上做出过突出贡献者的合作和交流而完成的。鉴于很多原创性的工作仍然散落在不同年份的研究期刊中，本书尝试把这些文献中的相关研究结合起来以飨读者。

与现有的极化成像雷达的著作相比，除了极化基本概念、数据处理方法和典型应用算法模型外，基于统一理论描述的散射机理研究是本书的突出特点。作者从电磁波的物理特性入手，围绕波的去极化（Depolarization）这个信息损失的随机过程，利用散射熵的概念量化分析去极化效应，深入浅出地阐述了极化和极化干涉技术基本概念中所蕴涵的物理意义以及贯穿其中的核心思想，对于读者理解极化和极化干涉技术的本质和基本特性大有裨益。本书第一次将波极化与雷达干涉的主题结合在一起，并重点论述了两者融合后的极化干涉技术的重要发展。我们的确能从书中看到极化干涉技术比简单的极化和干涉技术相加有更大的优势和潜力，它开启了遥感应用中的新的可能性。该书的英文原版书超过 450 页，包括九章内容，分别是极化电磁波、去极化与散射熵、表面散射与体散射去极化、分解理论、雷达干涉技术概述、极化干涉理论、表面散射与体散射相干性、运用极化干涉进行参数估计，以及极化干涉技术应用。内容丰富详实，作者把长期的极化及极化干涉研究成果和素材进行了全面的综合和整理，并且对当前最新的研究进展和成果也进行了阐述，形成了系统的极化理论体系，是一本很有特点的极化雷达理论方面的著作。

Polarisation: Applications in Remote Sensing 与 *Polarimetric Radar Imaging: From Basics to Applications* 这两本书是世界范围内极化雷达领域的经典著作，中译本同属于“微波成像技术国家重点实验室译著系列”。其中，后者的中译本《极化雷达成像基础与应用》于 2013 年由电子工业出版社出版（书号：978-7-121-20266-7）。

由于 *Polarisation: Applications in Remote Sensing* 一书涵盖内容广，对读者的极化理论和数理基础要求比较高，为了帮助读者快速掌握其核心思路的发展、主要内容方法和重要结论，我们决定根据章节内容对英文版内容进行评注。评注人曾多次就章节关系、索引翻译及注释原则等问题与作者沟通交流，评注的形式和内容均得到了作者的高度认同。本书的评注工作主要由洪文、尹嫱、李洋完成，研究生郭胜龙、张晶晶等参与了部分工作。

评注版的作者序

It is a great pleasure to have this opportunity to introduce a new Chinese language version of my book. I offer my sincere thanks to the group of translators, especially Hong Wen and Qiang Yin of IECAS in Beijing for their patience and efforts in generating a coherent summary from the original wide ranging text. I appreciate their help in maintaining the spirit of the original book throughout their translation.

This does however provide a fine and timely opportunity to reflect on the original motivation and background for the text, and to assess where it now stands in the fast developing area of remote sensing employing combinations of polarimetry and interferometry. I believe it still offers a unique and comprehensive approach to the topic, but how for example would the chapters change in content, and what new chapters would be included if I were starting this project in 2014 instead of 2008? In the next few paragraphs I will reflect on the historical motivations for the book and also try to cover some of the more recent developments in the subject.

The original motivation was to write a technical book suitable for graduate student level that merged the two disciplines of polarimetry and interferometry, to give one of the first didactic accounts of the subject. The approach was of course a personal one, but pulled together many disparate strands of work scattered over more than twenty years of academic publications on the topic by various authors and groups around the world. The idea was to demonstrate clearly and rigorously how polarimetric interferometry has its roots in electromagnetic scattering theory, and how the constructs of complex matrix algebra could be used to efficiently extract information on the physics of scattering from the signals and images used in radar and optical remote sensing.

To this end I hope the book is largely successful, but it does contain a lot of theory and reader feedback so far has, in roughly equal measure, been both great pleasure and horror at the prospect. It is this high math content that led us to adopt this slightly unusual translation approach of Chinese language summary together with the original text. In this way we hope the reader will get maximum benefit. When writing a book, one always keeps in mind a typical reader who shadows the author through development of the text. Mine was always motivated to understand the fundamentals of the subject and encouraged to work through the chapters to see how the themes develop before moving on to use the techniques in data analysis or applications. This for sure is challenging given the scope and novelty of topics, but it remains my belief that the rigor of such an approach pays dividends in the end, with readers better able to quickly see connections between the basic ideas here presented and also understand the constant stream of new innovations coming into the subject.

Turning now to more recent developments since the book's publication and how they relate to the original content, I would offer three important up-dated themes: Generalized Decomposition Theory, 3-D imaging or Polarimetric Tomography and Differential Polarimetry. I now take this opportunity to present a brief discussion of each and how they relate to the existing book structure, with some extra updated references provided for suggested further reading.

1. Generalized Decomposition Theory

There have been several new developments in polarimetric matrix decomposition theory since this book was first published (see chapter 4), extending across all three main types of decomposition, namely eigenvector based, model based and matrix product factorizations. For example, both the Yamaguchi[1,2] and van Zyl[3] model approaches have been extended since writing and now are more comprehensive in their coverage. The Yamaguchi approach has been extended to account for a full T3 matrix i.e. with nine model elements and the van Zyl approach centered on estimating multi-parameter volume scattering components by enforcing a positive semi-definite coherency matrix, while maximizing the volume scattering power. Although these most recent methods are not here presented, the basic elements and building blocks of all such model decompositions are developed in this book and so the reader can obtain a good basis for quickly understanding these and any further new developments that may come.

There have also been important developments in optical decomposition theory, which include natural extensions into bistatic scattering and would certainly be included in an extension of chapter 4. These cover both model based approaches but also an elegant generalization of eigenvector decompositions[4]. Indeed, these methods have all been recently connected through the topic of generalized decomposition theory[5], which uses a rank decomposition of $N \times N$ coherency matrices to unite all model, eigenvector and product decompositions. Again the seeds of this idea are already covered in chapters 3 and 4. Some important recent theoretical developments include explicit parameterization of the eigenvectors of 3×3 and 4×4 Hermitian matrices [4,6], as introduced in chapter 2 (but not fully developed there) and in Mueller matrix product expansions beyond the classical polar decomposition described in chapter 1[4,7]. I would recommend readers seek out these publications as follow up to the material in this book.

2. Polarimetric tomography

The use of polarisation for 3-D radar imaging has also seen several important developments since the original publication of this book. Currently the book does introduce one such technique, coherence tomography in chapters 8 and 9, and the structure function there described plays an important role in all such techniques. Again these would provide material for a new chapter 8, where coherence tomography would be extended and unified with multi-baseline tomographic techniques. In particular I would highlight two key recent developments in this area. The Capon high-resolution spectral analysis technique has been recently extended to full 3-D estimation of the polarimetric coherency matrix[8], allowing 3-D mapping of variations in polarised and depolarised matrix components. Secondly, the algebra of polarimetric decomposition in radar tomography has also been elegantly developed in [9]. Both of these are important milestone developments towards truly 3-D polarimetry.

3. Differential Mueller/Coherency analysis

This topic, which involves the generation of a differential calculus of depolarised wave scattering, has been recently further developed in [10,11], building on original work by Azzam in 1978 (as already referenced in this book). These studies present a formal connection between the Jones propagation calculus and Mueller/coherency matrix analysis presented here in chapters 1 and 2. In this way propagation through complex systems, where waves become depolarised on their way through materials, can be treated and decomposed into elementary processes in a physically (and mathematically) consistent manner. This again is an important future research topic, with potential applications across many areas, including differential time series analysis of polarimetric radar data. While some elements of the required differential calculus are presented here, any future edition would include a fuller treatment of this important new topic in a separate chapter. In radar imaging there have been extensive developments in a related area, the application of filtering and classification to time series analysis[12]. As more radar satellite systems have been launched they have made available long time series data stacks of polarimetric interferometric imaging data and the optimum ways to process these stacks represents one of the most challenging and active areas of research at the current time.

In conclusion, I would say that while it is impossible for any single book to keep up with the pace of development in polarimetric interferometry, this in my view is a good thing. It reflects the ongoing importance and global interest in this new technology and again I believe reinforces the need for books that develop the fundamentals of the subject, so enabling quick adaptation to change. I believe that this book is one such example and I hope you, the reader, will gain some improved insight into the subject.

Shane R. Cloude

April 2015

Suggestions for Further Reading

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Preface

An alternative title considered for this book was *Which Way is Up? Questions and Answers in Polarisation Algebra*. On advice it was rejected in favour of a more conventional approach. Still, it is a good question. Which way is up? A question with a literal scientific interpretation — namely, how to define vertical in a free reference frame for electromagnetic waves, but also one with a colloquial interpretation about the best route to progress. At a technical level this book is concerned with the answer to the former, but hopefully will serve to promote in the reader some idea of the latter. It arises from over twenty years' personal experience of research in the topic, but also through the privilege of having met and collaborated with many of those who made fundamental contributions to the subject. Much of this original work remains, unfortunately, scattered in the research literature over different years and journals. This book, then, is an attempt to bring it all together in a didactic and coherent form suitable for a wider readership.

The book aims to combine — I believe for the first time — the topics of wave polarisation and radar interferometry, and to highlight important developments in their fusion: polarimetric interferometry. Here indeed we shall see that the whole is greater than the sum of the parts, and that by combining the two we open up new possibilities for remote sensing applications.

It is intended as a graduate level text suitable for a two-semester course for those working with radar remote sensing in whatever context, but is also aimed at working scientists and engineers in the broad church that is remote sensing. Hopefully it will also appeal to those working in optical physics — especially polarimetry and light scattering — and to mathematicians interested in aspects of polarisation algebra.

Before reviewing the structure of the book, certain spelling requires clarification. Polarisation or Polarization? The usual response is that British English uses 's', and American 'z'. However, in this text we reserve spelling with 's' for the property of a transverse wave, while we use 'z' for the effect of electromagnetic fields on matter. Hence waves remain polarised while matter is polarized. In this way we take advantage of both forms.

Chapter 1 first provides an introduction to the physical properties of polarised waves using the formal machinery of electromagnetic wave theory. The idea is to provide motivation and a foundation for many concepts used in later chapters. For example, the concepts of matrix decomposition, the use of the Pauli matrices in wave propagation and scattering and, most importantly of all, the idea of using unitary matrices to form a bridge between mathematical descriptions of polarisation in terms of complex and real numbers, are all introduced in this chapter. This is in addition to the more prosaic elements of polarisation theory, such as the polarisation ellipse, the Stokes vector, and the Poincaré sphere, all of which are covered. The chapter is organized around three main themes: how to generate polarised waves and describe them in various coordinate systems, how to represent the propagation of such waves between two points A and B, and finally how to describe their interaction with particles via the process of scattering. The idea throughout is to develop the concept of the 'memory' imprinted on a wave of its original polarisation and how this may be lost through the complexities of propagation and scattering.

This idea of 'loss of memory' is developed further in Chapter 2, where stochastic effects are treated in more detail. We start by considering the coherency matrix of a wave and show how it leads to the wave dichotomy; namely, two different ways in which to model the loss of polarisation information to noise. This then opens up a new approach to describing the effects of noise, not just on a freely propagating wave but also on a scattering system as a whole via the concept of scattering entropy. Entropy is an important concept in this book and here we show how entropy from a generalized coherency matrix description can be formally linked to the classical Mueller/Stokes formulation. This leads, for example, to a formal test for isolating the set of physical Mueller matrices from the much wider set of 4×4 real matrices — something which is quite difficult to do from the Mueller calculus itself. We also show how the entropy concept can be applied to multiple dimensions, including general bistatic or forward scattering, so freeing it from the important but special case of backscatter widely used in radar.

Chapter 3 was in many ways one of the most difficult to write. Here we attempt to apply the ideas of entropy to electromagnetic models of surface and volume scattering (where polarization becomes important). What makes it difficult is the sheer scope of the problem. There are so many such models that they perhaps deserve a whole book to themselves. Instead we concentrate on a few simple models to convey the key ideas, and also link to developments in later chapters on decomposition theory and interferometry. Given that the main application of this book is to microwave scattering, we further concentrate on low-frequency models, whereby the wavelength is quite large compared to the size of the scattering feature, which has the further advantage that closed-form analytic formulae are available to calculate, for example, the scattering entropy. Having discussed this, we provide some treatment of high-frequency models and how they differ in polarisation properties from the low-frequency approach.

Chapter 4 deals with the important new topic of decomposition theorems. These now have widespread application in microwave remote sensing, and basically seek to isolate or separate various contributions in a mixture of scattering processes. The most important such idea is to separate surface from volume scattering. Microwaves have the ability to penetrate vegetation and other land cover (snow, ice, and so on) and thus generally incorporate a complicated mixture of processes in the scattered signal. Decomposition theorems are an attempt to separate these and hence improve interpretation and parameter retrieval in quantitative remote sensing applications. There are two basic classes of decomposition — coherent and incoherent–and within each class several authors have proposed different models. Here we provide a unified survey of all such methods and illustrate their various strengths and weaknesses by linking their physical structure to the ideas developed in earlier chapters.

One key conclusion we will see from the first four chapters is that entropy or 'loss of memory' about polarisation is often linked directly to the randomness of the scattering medium, and that the remote sensing 'observer' has little control over this. This is problematic for applications, for example, in vegetation remote sensing, where randomness in the volume leads to loss of polarisation information. A key idea for the second part of the book is therefore how to achieve some kind of entropy control in remote sensing of random media. One way to do this is to employ interferometry. Radar interferometry is a mature established topic, so in Chapter 5 we provide only a brief introduction for those not familiar with the key concepts. However, the chapter also contains one or two novel developments required in later chapters. In particular we develop a Fourier-Legendre series approach to a description of coherent volume scattering in interferometry. This then provides a bridge between the two halves of the book, and allows us to consider, in Chapter 6, the combination of polarisation diversity with interferometry.

The combination of polarisation diversity with radar interferometry has been a key development over the past decade. It was first made possible from an experimental point of view by late additions to the NASA Shuttle imaging radar mission SIR-C in 1994, and since then has evolved through a combination of theoretical studies and airborne radar experiments. In Chapter 6 we outline the basic theory of the topic, showing how to form interferograms in different polarisation channels before considering mathematically the idea of coherence optimization, whereby we seek the polarisation that maximizes the coherence (or minimizes the entropy). In this way we provide a link with earlier chapters by showing how polarimetric interferometry leads to a form of 'entropy control', even in random media applications.

In Chapter 7 we therefore revisit the ideas of surface and volume scattering first introduced in Chapter 4, but this time we investigate their properties in both interferometry and polarimetry. This is built around the idea of a coherence loci, a geometrical construct to bound the variation of interferometric coherence with polarisation, and closely related to the coherence region, the latter taking into account spread due to statistical estimation of coherence from data. Given the importance of surface/volume decompositions in microwave remote sensing, we treat in some detail the two — layer scattering problem of a volume layer on top of a surface and use it to review several model variations that are found in the literature.

In Chapter 8 we use these ideas to investigate the inverse problem: the estimation of model parameters from observed scattering data. We concentrate on the two-layer geometry and investigate four classes of problem. We start with the simplest: estimation of the lower bounding surface position, which is a basic extension of conventional interferometry and allows us, for example, to locate surface position beneath vegetation and hence remove a problem called vegetation bias in digital elevation models (DEMs). We then look at estimating the top of the layer, which corresponds in vegetation terms to finding forest height. This is an important parameter for estimating forest biomass, for exam- ple, and in assessing the amount of carbon stored in above-ground vegetation. We then look at the possibility of imaging a hidden layer using polarimetric interferometry. In this case we wish to filter out the scattering from a volume layer to image a surface beneath. The next logical step is to image the vertical variation of scattering through the layer itself, and this we treat as the topic of polarisation coherence tomography or PCT, which combines the Fourier-Legendre expansion of coherent volume scattering with decomposition theory in an interesting example of what can happen when two of the major themes of this book — polarisation and interferometry — are fused.

Finally, in Chapter 9 we turn attention to illustrative examples of these theoretical concepts. By far the most important current application area is in radar imaging or synthetic aperture radar (SAR), and so we begin by reviewing the basic concepts behind this technology, always highlighting those issues of particular importance to polarisation. We treat a hierarchy of such imaging systems, from SAR to POLSAR and POLInSAR, and then consider illustrative current applications in surface, volume, and combined surface and volume scattering.

We then present supportive material in three Appendices. In the first we provide a basic introduction to matrix algebra. This is used extensively in descriptions of polarised wave scattering, and is provided here to help those not familiar with the terminology and notation employed.

As mentioned earlier, one key idea in this book is the role played by uni-tary matrix transformations in linking (or mapping) different representations of polarisation algebra. For this reason, in Appendix 2 we provide a detailed mathematical treatment of the algebra behind such relationships, introducing concepts from Lie algebra, group theory, and matrix transformations to illus trate the fundamental relationships between complex and real representations of polarised wave scattering.

Finally, in Appendix 3 we provide a short treatment of stochastic signal theory as it relates to polarisation and interferometry. Here we treat aspects of speckle noise in coherent imaging, and show how estimation errors impact on estimation of scattered field parameters in remote sensing.

This book is the culmination of many years of study and research, and acknowledgement must be given to those many colleagues and students who provided the impetus and curiosity to study and develop these topics. Acknowledgements and thanks are extended to the European Microwave Scattering Laboratory (EMSL) at Ispra, Italy, for their permission to use data from their large anechoic chamber facility; to the German Aerospace Centre (DLR) in Oberpfaffenhofen, Germany, for provision of airborne radar data from their E-SAR system; and to Michael Mishchenko of NASA Goddard Space Center, USA, for provision of his latest numerical simulations of multiple scattering from particle clouds. Thanks also to the Japanese Space Agency (JAXA) for provision of the PALSAR satellite data used in Chapter 9. All these datasets play a vital role in illustrating the theory outlined in this book, and, I believe, help enormously in clarifying what would otherwise remain abstract concepts. Key personal thanks go to five colleagues in particular. Firstly, to Professor Wolfgang Boerner of the University of Illinois, Chicago, USA. His early vision and boundless energy have inspired several generations of researchers in these topics, including my own early studies as a PhD student. Secondly, thanks to Professor Eric Pottier of the University of Rennes, France. Our early collaboration on radar polarimetry, and particularly on decomposition theory, was inspiring, and has lead, I am pleased to say, to a lifelong friendship and collaboration. Thanks also to Drs Irena Hajnsek and Kostas Papathanassiou of the German Aerospace Centre, DLR. Their support and their contributions to the development of polarimetric interferometry have been key in the maturation of the subject. Finally, however, I would like to acknowledge the late Dr. Ernst Luneburg of DLR, Germany. His combination of scholarship and passion for the application of mathematics to remote sensing was the true inspiration for me to write this book, and I feel I can now finally answer his oft-posed question: '*Wo ist das Buch?*'

Shane R. Cloude

January 2009

前　言

最初，我给这本书起名为 *Which Way is Up? Questions and Answers in Polarisation Algebra*。虽然未被采纳，但这仍然是一个好问题。Which way is up? 从科学问题的角度理解，即如何在自由参考系中定义电磁波的垂直方向。从口语表达的角度理解，即什么是最好的发展途径。本书在技术层面回答了第一个问题，但也希望能够启发读者关于后一个问题的思考。本书是基于作者 20 余年的相关研究经验，以及与那些在此领域做出过突出贡献者的合作和交流而完成的。鉴于很多原创性的工作仍然散落在不同年份的研究期刊中，本书尝试把这些文献中的相关研究结合起来以飨读者。

本书结合了波极化与雷达干涉的主题，并重点论述二者融合后的重要发展。我们的确能从书中看到极化干涉技术比简单的极化和干涉技术相加有更大的优势和潜力，它开启了遥感应用中的新的可能性。

本书适合作为雷达遥感领域研究生的两个学期的教学用书，也可以作为遥感领域各分支中科研人员和工程师的参考书。希望那些从事物理光学研究，特别是极化与光散射方面，以及对极化代数感兴趣的数学研究人员也能从本书得到启发。

在总览全书结构之前，需要澄清特定拼写的含义。极化译作 Polarisation 还是 Polarization？通常会认为英式英语使用 ‘s’，美式英语采用 ‘z’。然而，本书对于电磁波的性质保留 ‘s’，对物质的电磁场效应使用 ‘z’。因此波的极化是 polarised，而物质的极化是 polarized。这样就利用了两种形式。

第 1 章运用电磁波理论的方法介绍了极化波的物理特性，为后续章节的诸多概念准备了基础。例如，矩阵分解的概念、Pauli 矩阵在波传播与散射中的使用，以及作为极化的数学描述之桥梁的最重要的酉矩阵，都在本章中有所介绍。此外，还覆盖了极化理论中更实用的部分，例如极化椭圆、Stokes 向量和 Poincaré 球。本章围绕以下 3 个主题进行组织：如何生成极化波并在不同坐标系中描述它们，如何表征这些波在两点之间的传播，以及如何描述散射过程中它们与物质粒子的相互作用。但有一个思想贯穿始终，即建立一种能留在波原始极化状态上的“记忆”概念，以及这种“记忆”怎样在复杂的波传播和散射过程中丢失。

“记忆丢失”的概念在第 2 章中逐步展开，并详细讨论了其中的随机效应。从讨论波的相干矩阵开始，引出波的二分法，也就是对极化信息丢失变为噪声这一过程建模的两种不同方法。这是描述噪声效应的一种新方法，不仅适用于自由传播的波，通过建立散射熵的概念也可用于发生散射的整个系统。熵是本书的一个重要概念，这里给出了熵如何从一般相干矩阵形式联系到经典的 Mueller 或 Stokes 表示法。进而引申出能否从 4×4 实矩阵集

中分离出物理 Mueller 矩阵集的问题，因为它很难从 Mueller 计算法本身解决。同时也指出了怎样把熵的概念应用到多维，包括一般的双站或前向散射，不再局限于后向散射情况。

第 3 章在很多方面来讲都是最难写的。这里尝试将熵的思想应用到表面和体散射的电磁模型中（极化就变得更重要了）。困难之处在于问题本身涉及的范围。这类的模型非常多，可能需要一整本书来阐述。本书集中在一些简单的模型上来传达其中的核心思想，并与后续章节中论述的分解理论和干涉相联系。鉴于本书的主要应用是微波散射，因而集中在低频模型，即波长远大于散射特征的尺寸。此外还有一个优点是能得到诸如熵这样封闭形式的解析表达式。在上述内容基础上，亦提供了高频模型的一些处理办法，以及它们在极化特性方面与低频模型的不同之处。

第 4 章论述分解理论中的重要问题。分解理论已经在微波遥感领域得到了广泛的应用，主要是从散射过程的混合体中分离出不同类型散射分量的贡献。其中最为重要的是从体散射中区分出表面散射。微波有穿透植被和其他陆地覆盖物（雪，冰等）的能力，因此散射信号通常是集合了各种过程的复杂混合物。分解理论试图把它们分开，因而改善对定量遥感应用的理解和参数获取结果。分解的两个基本类型是相干和非相干分解，针对每类分解都有若干作者提出了不同的模型。本书对这些模型进行总览，将其物理结构与前述章节中的思想联系起来，阐述各自的优缺点。

前 4 章的主要结论是极化熵和“记忆丢失”通常与散射介质的随机性直接联系在一起，而遥感的“观测器”对此只有很少的控制。这对应用来说存在问题。例如，在植被遥感中，植被体的随机性导致极化信息的丢失。因此，本书第二部分的关键思想是如何在某种程度上控制随机介质遥感中的熵。一种方法是采用干涉。雷达干涉是一种发展较为成熟的技术，第 5 章给不熟悉其主要概念的读者提供了简单的介绍。此外，本章也包含了后续章节所需要的技术。特别是发展了一种 Fourier-Legendre 级数方法来描述干涉中的相干体散射。因而本章在全书两大部分之间架起了桥梁，使得第 6 章中探讨极化多样性与干涉的结合成为可能。

极化多样性与雷达干涉的结合在过去 10 多年里得到了重大发展。它最初是在 1994 年美国国家航空航天局的航天飞机成像雷达任务 SIR-C 上实现的。此后，理论研究和机载雷达实验相结合，逐步发展起来。第 6 章概述了这个主题的基本理论，指出如何用不同的极化通道形成干涉条纹图，再从数学角度研究相干最优思想，即寻找能使相干性最大（或熵最小）的极化状态。通过这种方法与前述章节进行联系，说明了极化干涉如何给出一种“熵控制”的形式，包括在随机介质中的应用。

第 7 章回顾第 4 章介绍过的表面散射与体散射的概念，但侧重于其极化和干涉特性。本章围绕相干性轨迹的思想展开，这是一种显示干涉相干性随极化变化的几何方法，与相干区域紧密联系。相干区域给出了数据相干性统计估计的范围。鉴于微波遥感中的表面/体散射分解的重要性，本章详细论述一层地表覆盖一层植被的两层散射问题，并借此回顾文献中各种模型的异同点。

第 8 章运用上一章的思想研究反演问题：即从观测到的散射数据估计模型中的参数。本章集中讨论两层几何构型及四类问题。首先，从最简单的估计地表的下层边界位置开

始，它是常规干涉基本问题的延伸，可以通过确定植被层下地表的位置而去除数字高程模型（DEM）中由于植被引起的偏差。接着通过模型中对植被层的估计获得树高。这是森林生物量估计中的重要参数，例如地上植被碳储量的评估。然后，研究利用极化干涉探测隐藏分层的可能性，如通过滤除上层体散射的影响以获得关于下层地表的描述。下一步是描述层中间的垂直方向上散射的变化情况，即极化相干层析（PCT）问题。这个问题把相干体散射的 Fourier-Legendre 展开式与分解理论联系在一起，是极化与干涉两大主题融合所产生的具体实例。

最后，第 9 章把注意力转向理论概念的说明实例。到目前为止，最重要且最相关的应用领域是雷达成像或合成孔径雷达，所以本书从回顾这一技术背后的基本概念开始，始终强调极化对于这些问题的特殊重要性。这样，成像系统就可以看成层级式的，即从合成孔径雷达（SAR）到极化合成孔径雷达（POLSAR）再到极化干涉合成孔径雷达（POLInSAR），然后考虑在表面散射、体散射以及二者结合的散射上的应用实例。

此外，本书还给出了 3 个补充附录。附录 1 就广泛应用在极化波散射描述中的矩阵计算进行了基本介绍，主要是为不熟悉本领域术语和符号的读者提供帮助。为了说明酉矩阵变换在极化计算的不同表示形式中起到的作用，附录 2 提供了相关代数运算的详细数学表达，引入了 Lie 代数、集合理论和矩阵变换等概念来说明极化波散射的复数与实数表征间的基本关系。附录 3 是随机信号理论概述，帮助理解极化与干涉间的相互联系。此外，附录 3 还阐述了相干成像中斑点噪声及遥感系统估计误差对散射场参数估计的影响等。

本书积累了多年的学习和研究成果，因此有必要向那些为本主题的发展贡献了力量的同事和学生致谢。同时感谢位于意大利 Ispra 的欧洲微波散射实验室（EMSL）提供大型暗室设备数据；感谢位于德国 Oberpfaffenhofen 的德国宇航中心（DLR）提供 E-SAR 系统机载数据；感谢美国国家航空航天局（NASA）Goddard 空间中心的 Michael Mishchenko 提供质子云多重散射的最新数值仿真结果。还要感谢日本空间局（JAXA）提供的 PALSAR 卫星数据（在第 9 章中采用）。所有这些数据集在阐述本书理论的过程中起到了至关重要的作用。我相信，如果没有它们，很多理论仍停留在抽象概念的阶段。

此外，我个人特别感谢五位同事。首先是美国芝加哥伊利诺伊大学的 Wolfgang Boerner 教授。他超前的视野和无尽的能量激发了本领域好几代的研究人员，包括本人早期作为博士研究生的工作。第二位是法国雷恩大学的 Eric Pottier 教授。我们早年在雷达极化，特别是分解理论上的合作非常愉快。更令人欣慰的是，它带来了我们一生的友谊与合作。同时感谢德国宇航中心的 Irena Hajnsek 和 Kostas Papathanassiou 博士。他们对极化干涉技术发展的支持与贡献对本领域的成熟起到了关键作用。最后，我要感谢德国宇航中心的 Ernst Luneburg 博士。他将数学应用到遥感中的学识和热情真正激励了我撰写本书，现在我认为可以回答他经常提出的那个问题：‘Wo ist das Buch?’

Shane R. Cloude

目　录
CONTENTS