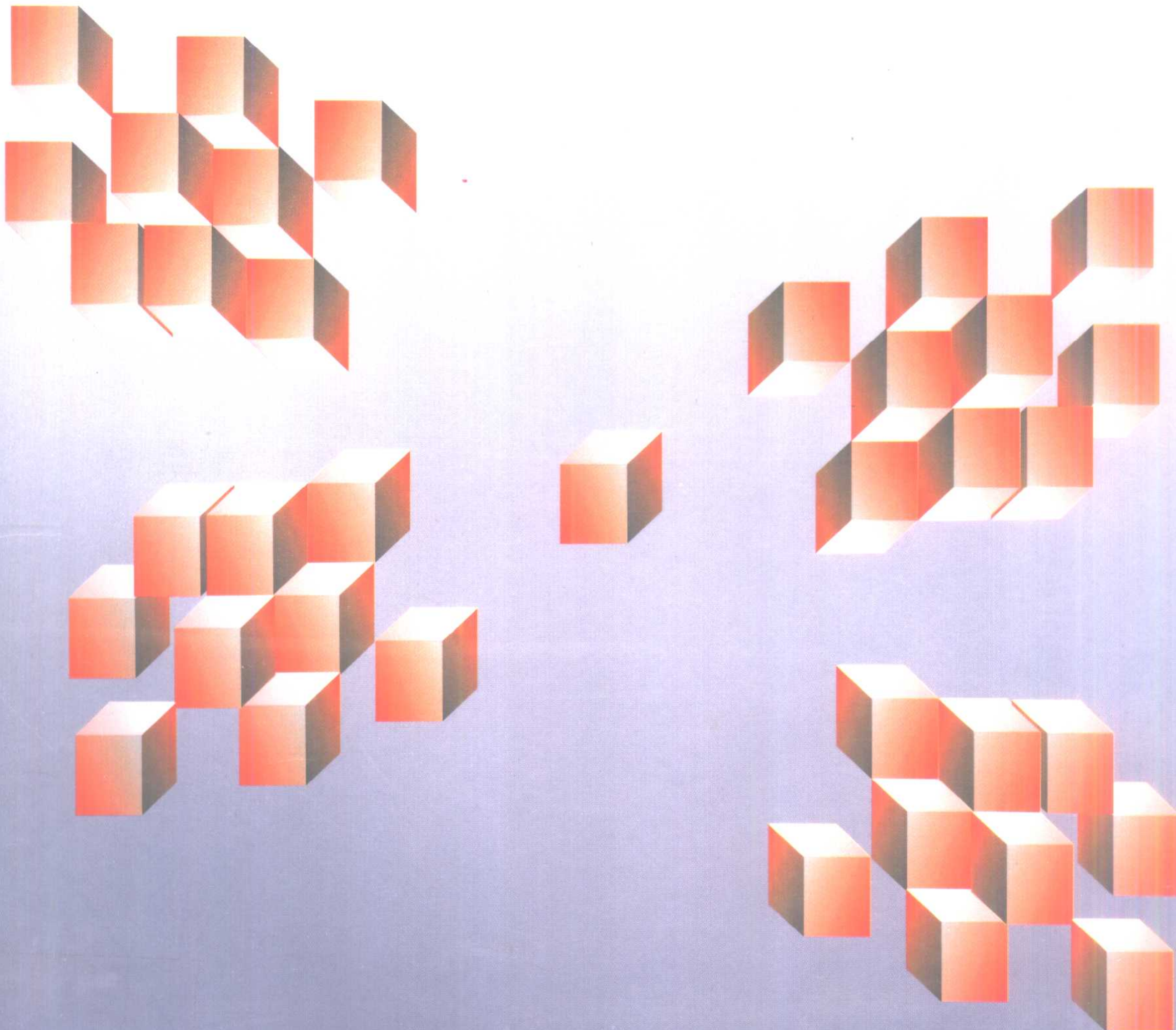
电磁散射和热辐射的遥感理论

金亚秋 著



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内容简介

本书从电磁波散射、热辐射和传输的基本原理出发，讨论了当今遥感理论的几个主要研究方向：随机离散粒子和连续随机介质的矢量辐射传输理论，随机介质中波的解析理论，随机粗糙面的散射理论以及在大气云和降水、地表植被、森林、冰雪、海冰、海洋等主被动遥感中的应用和实验数据的分析比较。本书系统地总结了作者十年来从事遥感理论的研究成果，也包括了国际同行在一些问题上的论述，将理论、计算方法、数值结果、实验比较与分析结合起来，系统详细地介绍了当今遥感理论的主要内容，使读者能了解和掌握遥感理论模式的研究及其数值方法、主要的结论和进展。

本书可作为电磁波散射和传播、无线电物理、通讯、大气、陆地和海洋遥感、地理环境遥感、地球和大气科学、航天科学、应用物理、统计光学、统计声学以及有关交叉学科的科学工作者的研究参考书和相应专业的高年级大学生和研究生的教学参考书。

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前　　言

近二十年来，随着无线电电子学、航天科学和计算机技术的发展，遥感已成为人类探索自然环境、监视和估计地球资源、了解全球性物理化学和生物系统变化的最重要的科学技术成就和最为有效的手段之一．随着人类活动对环境日益增大的压力，对全球性气候和生态变化的了解，遥感科学的发展将变得更为迫切．遥感发展至今的一个重要问题是如何定量地理解遥感数据所能提供的丰富信息，而不仅是依靠经验地定性判读．

电磁热辐射和入射电磁波(可见光、红外、毫米波、微波)与遥感对象和环境的相互作用为我们提供了被动和主动遥感的丰富信息．要充分地理解遥感图象和数据的丰富的信息，必须深入理解和研究电磁波与遥感对象和环境相互作用的机理，发展定量的数理模式和数值计算仿真方法．自然界中遥感对象(大气、云雨、土壤、植被、冰雪、海洋等)可以看作是离散的散射体组成的随机介质，或者介电常数随机起伏的连续随机介质．散射体的介电特性、大小、形状、空间取向及其分布，或者介电常数起伏统计方差、相关函数，以及随机介质的多层复杂结构、平滑的或粗糙的界面等等，构成了随机介质基本的物理模型．研究随机介质中电磁波散射、热辐射及其传输的数学物理学理论及其数值计算方法，使我们能够得到主动遥感中各种极化的双站和后向散射系数、被动遥感中极化的辐射亮度温度，并建立起这些量与遥感对象介电的、几何结构的以及其它重要的特征性参数之间的定量的函数关系，进而为遥感数据的分析和利用、参数的反演等提供可靠的理论依据．它对进一步改善和发展遥感仪器，发展遥感的新方法、新手段，也具有十分重要的意义．其理论与方法对于生物组织诊断、工程材料测试、反演地球内部介电特性、复杂环境中目标识别、电子对抗中环境杂波的影响等以及在一些交叉学科中也具有广泛的应用前景．

遥感理论包括了随机介质的矢量辐射传输理论、波的解析理论、随机粗糙面的散射理论，以及在大气、云和降水、地表植被、森林、冰雪、海洋、海冰等主被动遥感中的应用等．本书从当今遥感理论的几个方面，总结了作者十多年来从事遥感理论研究的主要研究成果，也包括一些国外在有关问题上的论述，使读者能了解在该领域中研究的理论、方法及其进展．它的进一步深入的研究和广泛的应用，是我们今后共同要做的事，也是本书抛砖引玉的目的．

本书的第一章将给出各种形状和大小的单个散射粒子的散射振幅函数，它是第二章矢量辐射传输方程的基本知识准备．在第二章中，我们讨论了四个 Stokes 参数的矢量辐射传输 (VRT) 方程，给出随机分布的各种离散散射粒子 (Rayleigh、Mie 球形粒子、非球形粒子)和连续随机介质的 VRT 方程各组成成分：散射、吸收和消光系数、多次散射的相矩阵、热发射矢量的解析表达式，并对连续随机介质的相关函数及其相关长度进行了讨论．在第三章中，我们广泛地讨论了 VRT 方程的几种具体的解法，如迭代法、离散

坐标-特征值法、傅利叶变换法等等，以及这些方法在应用到大气降水，植被等具体的主被动遥感中的求解过程，参数选取的法则和与遥感数据的比较分析．对于一层非球形粒子的 VRT 方程，我们讨论了迭代法和 Mueller 矩阵，对全极化散射的理论作了分析，得到数值结果，并应用于植被的后向散射研究．在第四章，我们讨论多层耦合模型的 VRT 方程，并应用于农作物、森林植被的热辐射研究．当散射元在水平方向上分布不均匀时，要讨论多维的 VRT 方程，我们讨论了二维 VRT 方程的迭代解及其数值求解，并应用于大气云、降水和植被的热辐射．

在第五章中，从基本的 Maxwell 方程出发，讨论波的解析理论．利用平行分层随机介质的平均并矢 Green 函数，求解散射场的一阶矩（Dyson 方程），即平均场，以及二阶矩（Bethe-Salpeter 方程），即散射场强．得到双站和后向散射系数，并讨论在植被等遥感中的应用．同时，我们还应用非均匀耗散介质的起伏逸散定理，来研究土壤的热辐射遥感．作为波的解析理论的基础，介绍了波动方程的重正化和 Feyman 图、Dyson 方程和 Bethe-Salpeter 方程的 Feyman 图表示及其几种近似．当介电起伏为强起伏时，我们必须考虑强起伏理论．在第六章，我们阐明了强起伏理论的基础和方法，利用广义的 Born 近似，得到了双站和后向散射系数，并应用于冰雪的主动遥感．并进一步应用强起伏理论，推导出强起伏连续随机介质的 VRT 方程，讨论了并矢 Green 函数的极限行为和 δ 函数，并应用于冰雪和海冰的被动遥感中．然后，由二阶的广义 Born 近似，讨论了随机粒子相干散射产生的后向散射增强现象．

当散射粒子所占体积比大于 0.1 时，各个粒子的散射不再是相互独立的．散射的相干性必须要引进 VRT 方程中，这就是第七章的密集分布离散粒子的修正的 VRT 方程．从波的解析理论 Dyson 方程的具有相干势的准晶体近似（QCA-CP）和梯形近似的 Bethe-Salpeter 方程出发，利用密集粒子的成对分布函数，推导得到包括散射相干的密集分布离散粒子的 VRT 方程（DVRT），并讨论了 DVRT 方程的一些结果．然后综述了我们对星载遥感大气地表热辐射计算的 RADTRAN 程序的改进，形成了一个遥感模式计算系统．

随机粗糙面的散射也是随机介质中波散射及其遥感应用的一个重要组成部分．地表面、风驱动下的海面等都是复杂的粗糙界面．在第八章，首先讨论大尺度起伏(高频近似)粗糙面的 Kirchhoff 近似及其几何光学解，介绍了 KA 近似下准周期性的和倾斜的随机粗糙面的散射解．在给出小尺度起伏(低频近似)的微扰解之后，着重讨论了组合 KA 近似和微扰近似的双尺度模型及其求解，提出了一层随机离散散射粒子和双尺度随机粗糙面的复合模型，并应用于强风驱使下海面后向散射及其与风场的定量的函数关系．然后，讨论了随机粗糙面的多次散射，以及在后向散射方向上散射增强的解析理论和数值结果．

本书的研究成果是在国家自然科学基金委员会和霍英东教育基金会资助下完成的，并得到中国科学院科学出版基金的资助，作者表示感谢．作者特别感谢国家自然科学基金委员会地球科学部林海博士对本研究的支持和帮助，他促成了本书的完成；同时作者也感谢导师、中国科学院学部委员周秀骥教授和吕保维教授以及中国科学院大气物理研究所吕达仁研究员的关心和鼓励．作者在美国麻省理工学院（MIT）求学和在美工作期间，得到导师孔金瓯（J. A. Kong）教授，以及华盛顿大学曾亮（L. Tsang）教授，MIT

的 D. H. Staelin 教授、J. R. Melcher 教授、H. A. Haus 教授，纽约市立大学 M. Lax 教授，大气环境研究公司 R. Isaacs 副总裁的指导和帮助，在此特表示感谢；并对中国科学院大气物理研究所、复旦大学科技处和电子工程系对作者学习、研究和教学工作的支持表示感谢。作者也在此感谢妻子耿玲芝对作者的鼓励，并深切怀念已去世的辛劳一生的父母。

PREFACE

The substantial progress made during the last two decades in radio electronics, space science, and computer technology has turned remote sensing into one of the most effective tools for exploring, monitoring and assessing the natural environment and resourves, and for understanding the changes of global physical, chemical, and biological systems. Growing pressures on the environment from human activity and its sensitivity to climatic and biological changes make the development of remote sensing science more urgent than ever. One of the key issues is how to understand the overall information provided by remote sensing data, not only empirically or qualitatively, but quantitatively.

Interactions between electromagnetic waves (visible light, infrared, millimeter wave, and microwave) and the target-environment in passive and active remote sensing provide us with rich data. To fully understand these data, we must study and understand the interaction mechanism, and develop the quantitative mathematical-physical models and numerical approaches. Natural targets and environment in remote sensing (atmosphere, cloud and precipitation, soil, vegetation canopy, snow ice, ocean etc.) may be seen as a random medium containing discrete scatterers, or as a continuous random medium with dielectric fluctuation. The dielectric properties, scatterer size, shape, orientation and distribution, multi-layer structures, smooth or rough boundary surface and so on consist of the characteristic parameters of random media modeling. By studying the mathematical physics of electromagnetic scattering, thermal emission and transmission in random media, and developing numerical approaches, we can obtain the polarized bistatic and back-scattering coefficients in active remote sensing and the polarized brightness temperature in passive remote sensing, and then establish quantitatively their functional dependences on the dielectric, geometric and other characteristic parameters of target and environment. Remote sensing theory provides a reliable theoretical basis and guidance not only for data prediction and analysis, parameter retrievals, but also for improving and developing new remote sensors and novel approaches. The theory and method of remote sensing are also applicable to the biological diagonosis, material determination, inversion of the earth's internal properties, pattern recognition in complex background, environmental clutter in the electronic antagonism, and some other cross disciplines.

Remote sensing theory covers the vector radiative transfer of random media, analytic wave theory of random media, scattering from randomly rough surface, and applications in active and passive remote sensing of atmosphere, cloud and precipi tation, the earth terrain such as vegetation canopy, forest, snow, sea ice, ocean and so on. This book, starting from the basic principles of electromagnetic wave scattering, thermal emission and transmission, summarizes the author's 10 years of research in the remote sensing area, as well as the work of colleagues around the world. This book intends to make the readers to well understand the theories, approaches, and progress in remote sensing theory.

Chapter 1 gives the scattering amplitute functions of a single particle, which may have different shape and size. It is preparative knowledge for Chapter 2.

In Chapter 2, we discuss the vector radiative transfer (VRT) equation of four Stokes parameters. The analytic formulations of the scattering, absorption, extinction coefficients, and the phase matrix in the VRT equation for discrete scatterers (spherical Rayleigh, Mie, or nonspherical) and continuous random media are derived. The correlation function and correlation length of random media are discussed.

In Chapter 3, we discuss several approaches to the VRT equation, e.g. the iterative method, discrete-ordinate method and eigenanalysis approach. Fourier transformation method, etc. and applications in active and passive remote sensing of atmospheric precipitation and vegetation canopy. The rule of choosing parameters, and comparision with the experimental data are also illustrated. Using iterative method and the Mueller matrix, complete polarimetric scattering is discussed. Numerical results are applied to the backscattering study of vegetation canopy.

In Chapter 4, we discuss the coupled VRT equations for multi-layer of random media and apply them to the thermal emission from crops and forestry in passive remote sensing. When the scatterers are nonuniformly distributed in the transverse direction, we have to deal with the multi-dimensional VRT equation. We develop a numerical approach to solve a two-dimensional VRT equation and apply this method to the passive remote sensing of atmospheric precipitation and vegetation canopy.

In Chapter 5, from the basic Maxwell equations, analytic wave theory of random media is discussed. By using the mean dyadic Green's function (DGF) of stratified media, the first moment of scattering field (Dyson equation), i.e. the mean field, and the second moment (Bethe-Salpeter equaton), i.e. scattering intensity, are derived. The bistatic and backscattering coefficients are then obtained, and are applied to the active remote sensing of vegetation canopy. Meanwhile, employing the fluctuation-dissipation theorem for dissipative media, we study the thermal emission from moistured soil. As the basis of the analytic wave theory, the renormalized method of wave equation, the Feynman diagrams of the Dyson equation and Bethe-Salpeter equation, and approximations are introduced.

If dielectric fluctuation is strong, we should study the strong fluctuation theory. In Chapter 6, we illustrate the basis and approach of strong fluctuation theory. By using the distorted Born approximation, we obtain the bistatic and backscattering coefficients and apply them to the active remote sensing of snowpack, which is a strongly-fluctuated random medium. Furthermore, the VRT equation for a layer of strongly fluctuating, nonisotropic continuous random medium is derived. The limitation behavior of the DGF and delta function of singularity are discussed. The theory is then applied to the passive remote sensing of snow and sea ice. Then, carrying on to the second-order distorted Born approximation, backscattering enhancement due to the constructive interference from the boundaries is explained.

As the fractional volume of scatterers becomes larger (than 0.1), the assumption of independent scattering in the VRT equation will not be valid. Coherence of scattering should be taken into account. Chapter 7 is used to discuss the modified VRT equation for a layer of densely-distributed random scatterers (DVRT). Making use of the Dyson equation in quasicrystalline approximation with coherent potential (QCA-CP) and the Bethe-Salpeter equation in the ladder approximation, and using the pair distribution function, the DVRT equation is derived. Some results of the DVRT equation are discussed. Employing the surface models and numerical approaches, an improvement to RADTRAN code for space-borne remote sensing is reviewed. A simulation system is then completed.

Another important topic of random media is the scattering theory from randomly rough surfaces. The land surface, ocean surface driven by wind, and so on are rough surfaces. In Chapter 8, we first discuss the Kirchhoff approximation (KA) and geometric optics solution for large-scale rough surface, and KA solutions for quasi-periodic and skewed randomly rough surfaces. Then, after introducing the solutions of small perturbation approximation (SPA) for small-scale rough surface, we focus on the two-scale model, which combines KA and SPA. Then, we develop an approach to the VRT equation of random scatterers with two-scale rough boundary, and apply them to the sea surface with foam and white caps driven by strong wind. A quantitative relation between back-scattering and wind field is then obtained. Finally, we derive second-order scattering from rough surface, and discuss analytic and numerical results to illustrate the angular back-scattering enhancement from rough surfaces.

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目　　录

CONTENTS

第一章　单个散射粒子的散射振幅函数

在遥感理论模式中，遥感目标及其环境往往处理成随机分布的离散散射粒子或介电随机起伏的随机介质．比如，雨和云是空气背景中的水粒子；干雪是由冰粒子和空气背景所组成；湿雪还包含有居间的细小的水粒子；植被是由果实、干茎、枝叶等非球形粒子和空气背景所组成；海水是由空气泡、盐水杂质和冰所组成，如此等等．离散的散射粒子可具有大小分布的球形的或非球形粒子，非球形粒子还可有一定的空间取向分布；连续的随机介质可具有各向异性的、弱的或强的介电随机起伏．用这种随机介质的散射、吸收、传播和热辐射特征来描述遥感中波与遥感目标及其环境的相互作用，主动和被动遥感的观察结果，及其与各种物理参量之间的函数关系．在这一章里，我们首先给出单个散射粒子（球形 Rayleigh，Mie 粒子和非球形粒子）的散射振幅函数，即入射场和散射场的耦合关系．用散射振幅函数可计算多个独立地随机分布的散射粒子的散射和消光系数和电磁辐射强度多次散射的相矩阵，作为下一章辐射传输理论中各组成成分的基础．

§1.1　单个粒子的散射场和并矢 Green 函数

考虑在介电常数为 ε 的背景中入射波

$$\bar{E}_i(\bar{r}) = (\hat{v}_i E_{v_0} + \hat{h}_i \cdot E_{h_0}) e^{i\bar{k}_i\cdot\bar{r}} \equiv \hat{e}_i E_0 e^{i\bar{k}_i\cdot\bar{r}} \tag{1.1}$$

入射在介电常数 ε_s 体积 v_0 的一个散射粒子上(图 1.1)．在本书中，磁导率 μ 均假定为真空中的 μ_0．其中下标 i 表示入射波．传播波矢可写成

$$\bar{k} = k(\hat{x}\sin\theta\cos\phi + \hat{y}\sin\theta\sin\phi + \hat{z}\cos\theta) = k\hat{k} \tag{1.2a}$$

水平（TE 波)和垂直（TM 波)极化矢量分别定义为

$$\hat{h} = (\hat{z}\times\hat{k})/|\hat{z}\times\hat{k}| = -\hat{x}\sin\phi + \hat{y}\cos\phi \tag{1.2b}$$

$$\hat{v} = \hat{h}\times\hat{k} = \hat{x}\cos\theta\cos\phi + \hat{y}\cos\theta\sin\phi - \hat{z}\sin\theta \tag{1.2c}$$

可看出，若用球坐标（$\hat{r},\hat{\theta},\hat{\phi}$）来表示，则

$$\hat{v} = \hat{\theta},\ \hat{h} = \hat{\phi},\ \hat{k} = \hat{r}.$$

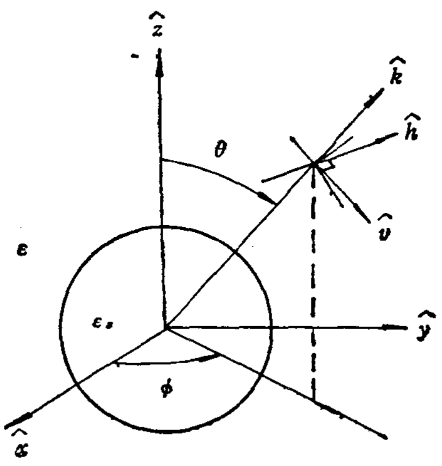

图 1.1　入射波和极化矢量

我们有 Maxwell 方程为

$$\nabla\times\bar{E} = i\omega\mu\bar{H} \tag{1.3a}$$

$$\nabla\times\bar{H} = -i\omega\varepsilon[\varepsilon_{sn}(\bar{r}) - 1]\bar{E} - i\omega\varepsilon\bar{E} \tag{1.3b}$$

其中 $\varepsilon_{sn}(\bar{r}) = \varepsilon_s(\bar{r})/\varepsilon$，下标 n 为归一化．方程（1.3b）中 $-i\omega\varepsilon[\varepsilon_{sn}(\bar{r}) - 1]$ 看作是