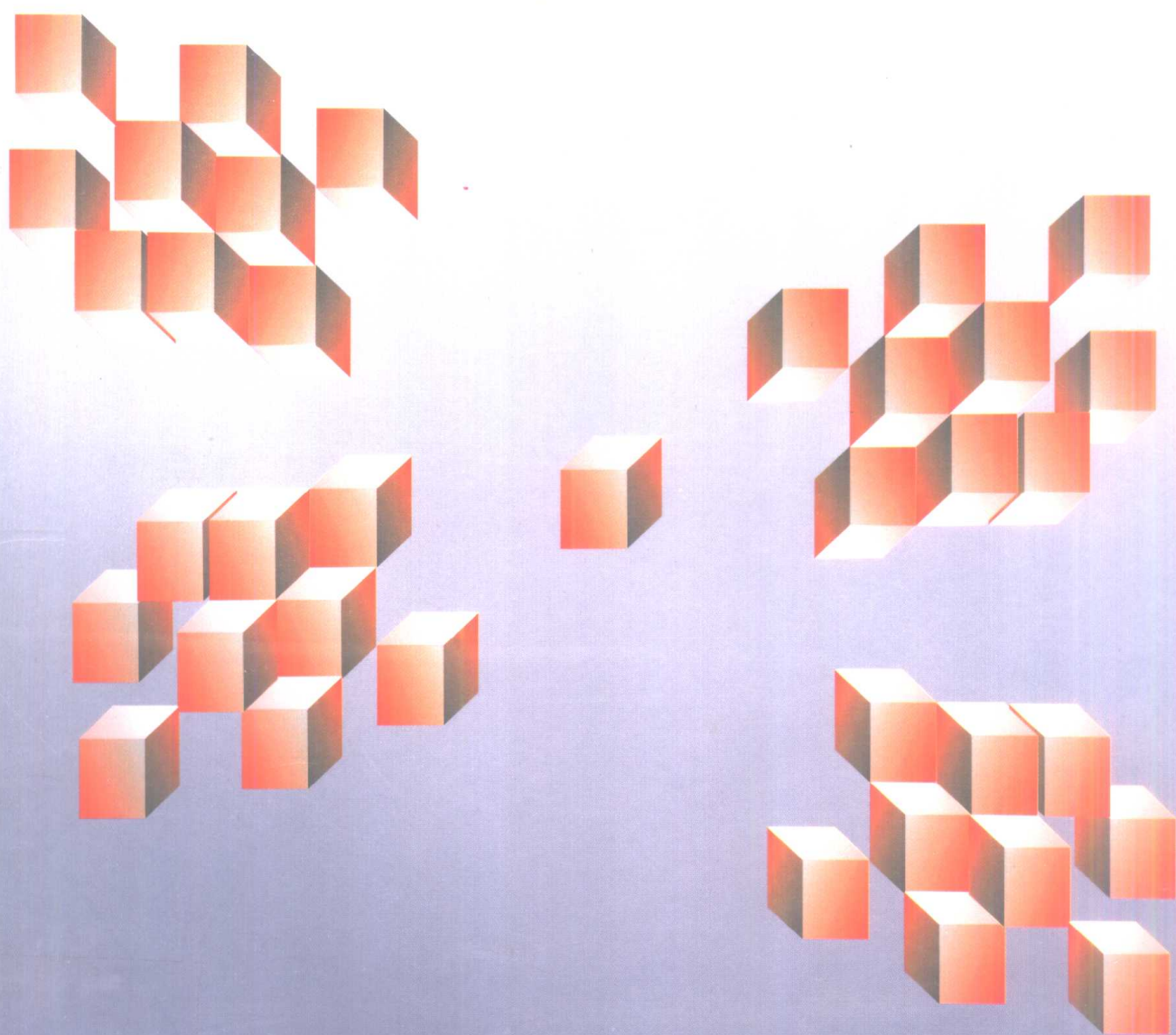
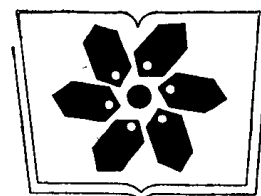


电磁散射和热辐射的遥感理论

金亚秋 著



科学出版社



中国科学院科学出版基金资助出版

电磁散射和热辐射的遥感理论

金亚秋 著

国家自然科学基金资助项目

霍英东教育基金会资助项目

科学出版社

1998

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。

电磁散射和热辐射的遥感理论

金亚秋 著

责任编辑 彭 斌

科 学 出 版 社 出 版

北京东黄城根北街16号

邮政编码:100717

中国科学院印刷厂印刷

新华书店北京发行所发行 各地新华书店经售

*

1993年7月第一版 开本:787×1092 1/16

1998年11月第二次印刷 印张:19 1/2

印数:801—1800 字数:433 000

ISBN 7-03-003626-3/P·688

定价:45.00元

(如有印装质量问题,我社负责调换〈科印〉)

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 Feynman 图、Dyson 方程和 Bethe-Salpeter 方程的 Feynman 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 resources, 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 diagnosis, 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 precipitation, 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,

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.

The research work in this book was supported by the National Natural Science Foundation of China (NNSFC) and Fok Ying Tung Education Foundation. The publication of this book is also supported by the Foundation of Science Press of the Chinese Academy of Sciences. The author is grateful to all of these support. In particular, the author wishes to express his great appreciation to Professor Lin Hai, Deputy Director of the Department of Earth Science of the NNSFC for the consistent support and help which made this book possible. The author also greatly appreciates his supervisor, Professor Zhou Xiuji of the Chinese Academy of Meteorology, and Professor Lü Baowei and Professor Lü Daren of the Chinese Academy of Sciences for their encouragement. The author is indebted to his supervisor, Professor J. A. Kong of MIT, and Professor L. Tsang of the University of Washington, Professor D. H. Staelin, Professor J. R. Melcher, Professor H. A. Haus of MIT, Professor M. Lax of CUNY, and Mr. R. Isaacs, Deputy President of Atmospheric and Environmental Research, Inc. (AER) for their guidance and help during his stay in the United States. He is also deeply grateful to the Institute of Atmospheric Physics of the Chinese Academy of Sciences, the Office of Science and Technology and the Department of Electronic Engineering of Fudan University for their support and help. Finally, the author wishes to thank his wife, Geng Lingzhi, for her encouragement and help in the family. And the author's deepest memory goes to his parents.

目 录

前言

| | |
|---|-----------|
| 第一章 单个散射粒子的散射振幅函数 | 1 |
| § 1.1 单个粒子的散射场和并矢 Green 函数..... | 1 |
| § 1.2 球形 Rayleigh 粒子 | 3 |
| § 1.3 Rayleigh 近似下的非球形粒子 | 3 |
| § 1.4 一般化的 Rayleigh-Gans 近似下的盘状针状粒子 | 6 |
| § 1.5 有限长圆柱体 | 10 |
| § 1.6 球形 Mie 粒子..... | 11 |
| 第二章 矢量辐射传输 (VRT) 理论 | 16 |
| § 2.1 Stokes 矢量 | 16 |
| § 2.2 热辐射和辐射亮度温度 | 18 |
| § 2.3 VRT 方程及其散射、消光系数和相矩阵 | 19 |
| § 2.3.1 VRT 方程及其各成分..... | 19 |
| § 2.3.2 Hueygen 原理 | 21 |
| § 2.3.3 光学定理和消光系数 | 23 |
| § 2.4 球形 Rayleigh 粒子的 VRT 方程 | 25 |
| § 2.5 球形 Mie 粒子的 VRT 方程 | 26 |
| § 2.6 非球形粒子的 VRT 方程 | 28 |
| § 2.6.1 相干波的特征传播波数和消光矩阵 | 28 |
| § 2.6.2 非球形粒子的相矩阵 | 31 |
| § 2.7 连续随机介质的 VRT 方程 | 34 |
| § 2.7.1 散射和消光系数、相矩阵 | 34 |
| § 2.7.2 相关函数的常用形式 | 36 |
| § 2.7.3 相关长度的实验确定 | 37 |
| § 2.7.4 相关长度的理论讨论 | 40 |
| 第三章 VRT 方程的解法及其在主被动遥感中的应用 | 46 |
| § 3.1 边界条件 | 46 |
| § 3.2 球形粒子 VRT 方程的迭代法 | 49 |
| § 3.3 大气降水的主动遥感和数值结果 | 53 |
| § 3.4 水的介电常数和其它常数的选取 | 61 |
| § 3.4.1 纯水、海水、冰的介电常数 | 61 |
| § 3.4.2 土壤的介电常数 | 63 |
| § 3.4.3 雨滴的大小分布 | 66 |
| § 3.4.4 大气气体的吸收系数 | 67 |
| § 3.5 离散坐标和特征值法 | 68 |

| | |
|--|------------|
| § 3.5.1 Gauss 求积法 | 68 |
| § 3.5.2 离散坐标的 VRT 方程及其特征值求解法 | 70 |
| § 3.5.3 大气降水的辐射亮度温度 | 72 |
| § 3.5.4 植被层的平均介电常数 | 75 |
| § 3.5.5 植被的辐射亮度温度 | 78 |
| § 3.6 球形粒子 VRT 方程的 Fourier 变换 | 79 |
| § 3.7 非球形粒子 VRT 方程的迭代法和全极化散射 | 87 |
| § 3.7.1 迭代法和一阶 Mueller 矩阵 | 87 |
| § 3.7.2 全极化散射的数值结果 | 90 |
| § 3.7.3 半空间的二阶 Mueller 矩阵 | 95 |
| 第四章 多层耦合的 VRT 方程和二维 VRT 方程 | 98 |
| § 4.1 多层随机介质耦合的 VRT 方程 | 98 |
| § 4.2 多层非均温的大气降水的热辐射 | 100 |
| § 4.3 多层耦合具垂直结构的植被森林的热辐射 | 104 |
| § 4.4 一层非均匀的随机介质的二维 VRT 方程 | 109 |
| § 4.4.1 离散形式的 Fourier 变换 | 109 |
| § 4.4.2 迭代解 | 111 |
| § 4.5 二维 VRT 方程的数值解 | 113 |
| 第五章 随机介质中波的解析理论 | 118 |
| § 5.1 平行分层介质的并矢 Green 函数 (DGF) | 118 |
| § 5.1.1 无界自由空间的 DGF 的 Fourier 展开 | 118 |
| § 5.1.2 平行分层介质的 DGF 的 Fourier 展开 | 120 |
| § 5.1.3 稳相法和远场近似下的 DGF | 123 |
| § 5.2 一阶 Born 近似下的后向散射 | 124 |
| § 5.3 多层随机介质的后向散射 | 131 |
| § 5.4 随机介质中有效介电常数的弱起伏条件 | 132 |
| § 5.5 起伏逸散定理和 WKB 解 | 134 |
| § 5.5.1 平行分层耗散介质的辐射亮度温度 | 134 |
| § 5.5.2 WKB 解 | 136 |
| § 5.5.3 具有连续温度和湿度廓线的土壤辐射亮度温度 | 139 |
| § 5.6 波动方程的重正化和 Feynman 图 | 143 |
| § 5.6.1 相干场二阶解的长期项 | 143 |
| § 5.6.2 Dyson 方程及其近似 | 144 |
| § 5.6.3 Bethe-Salpeter 方程及其近似 | 149 |
| 第六章 强起伏理论 | 154 |
| § 6.1 一层强起伏随机介质的散射 | 154 |
| § 6.1.1 广义 Born 近似下的散射强度 | 154 |
| § 6.1.2 有效介电常数和 δ - ξ 变换的意义 | 157 |
| § 6.1.3 离散散射粒子的相关函数 | 160 |
| § 6.2 双站和后向散射系数 | 161 |
| § 6.3 二阶去极化后向散射 | 166 |

| | | |
|-------------|---|------------|
| 附录 A6-1 | $\bar{\epsilon}_{01}^{\pm}(\bar{k}_p, z, z_1), \bar{\epsilon}_{11}^{\pm}(\bar{k}_p, z_1, z_2)$ 和 $\bar{F}_m(z)$ | 171 |
| 附录 A6-2 | $A_{\bar{v}v}^{\pm}(\phi)_{s,s',p,p'}$ 和 $A_{\bar{v}h}^{\pm}(\phi)_{s,s',p,p'}$ | 172 |
| 附录 A6-3 | 一些关系式 | 174 |
| § 6.4 | 强起伏随机介质中起伏逸散定理的应用 | 174 |
| § 6.4.1 | 零阶和一阶辐射亮度温度 | 175 |
| § 6.4.2 | 数值结果和讨论 | 179 |
| 附录 B6-1 | C_{mn}, H_n, V_n 和 U_n | 182 |
| § 6.5 | 强起伏各向异性连续随机介质的 VRT 方程 | 183 |
| § 6.5.1 | 相矩阵 | 184 |
| § 6.5.2 | DGF 中 δ 函数的系数的确定 | 187 |
| § 6.6 | 海冰的介电常数 | 190 |
| § 6.7 | 积雪和海冰辐射亮度温度的 VRT 数值结果 | 194 |
| § 6.8 | 二阶双站散射和后向散射增强 | 198 |
| 附录 C6-1 | $A_{hh}^{\pm}(\phi)_{s,s',p,p'}$ 和 $A_{vv}^{\pm}(\phi)_{s,s',p,p'}$ | 206 |
| 附录 C6-2 | $D_{hh}^{\pm}(\phi)_{s,s',p,p'}$ | 210 |
| 附录 C6-3 | 系数 C_{mn}^i | 212 |
| 第七章 | 密集分布离散粒子的辐射传输 (DVRT) | 214 |
| § 7.1 | 成对分布函数 | 214 |
| § 7.2 | 具有相干势的准晶体近似 (QCA-CP) 下的有效传播常数 | 216 |
| § 7.3 | QCA-CP 和梯形近似在能量守恒上的一致 | 222 |
| § 7.4 | 一层密集随机分布散射粒子的 DVRT 方程 | 223 |
| 附录 A7-1 | DVRT 中的 \bar{p}, \bar{j}_m | 229 |
| § 7.5 | 迭代解和界面反射的相干性 | 230 |
| § 7.6 | 热辐射 DVRT 方程的数值解 | 235 |
| § 7.7 | RADTRAN 程序的改进 | 238 |
| 第八章 | 随机粗糙面的散射 | 243 |
| § 8.1 | Kirchhoff 近似 (KA) | 244 |
| § 8.1.1 | KA 切平面近似和几何光学解 | 244 |
| § 8.1.2 | 准周期性随机粗糙面的 KA 近似解 | 250 |
| § 8.1.3 | 倾斜的随机粗糙面的 KA 近似解 | 254 |
| § 8.1.4 | 遮蔽函数 | 256 |
| § 8.2 | 微扰近似 (SPA) 解和双尺度模型 | 260 |
| § 8.2.1 | 微扰近似 (SPA) 解 | 260 |
| § 8.2.2 | 双尺度粗糙面的散射 | 262 |
| § 8.2.3 | 海面波高谱 | 267 |
| § 8.2.4 | 海面散射的数值结果 | 270 |
| § 8.3 | 具有随机粗糙界面的 VRT 方程的迭代解 | 273 |
| § 8.4 | 二阶散射和后向散射增强 | 277 |
| § 8.4.1 | 二阶散射场 | 277 |
| § 8.4.2 | 角度性的后向散射增强 | 282 |
| 附录 A8-1 | $F_{pq}^{(1+)}, F_{pq}^{(1-)}, F_{pq}^{(2+)}, F_{pq}^{(2-)}$ | 286 |
| 参考文献 | | 287 |

CONTENTS

PREFACE

| | |
|---|----|
| CHAPTER 1 SCATTERING AMPLITUDE FUNCTION OF A SINGLE SCATTERER | 1 |
| § 1.1 Scattering Field of a Single Scatterer and the Dyadic Green's Function | 1 |
| § 1.2 Spherical Rayleigh Particle | 3 |
| § 1.3 Nonspherical Particle Under the Rayleigh Approximation..... | 3 |
| § 1.4 Disk and Needle Particles Under the Generalized Rayleigh-Gans Approximation | 6 |
| § 1.5 Cylinder with Finite Length | 10 |
| § 1.6 Spherical Mie Particle | 11 |
| CHAPTER 2 VECTOR RADIATIVE TRANSFER (VRT) THEORY | 16 |
| § 2.1 Stokes Vector | 16 |
| § 2.2 Thermal Emission and Brightness Temperature | 18 |
| § 2.3 VRT Equation and Scattering, Extinction Coefficients, and the Phase Matrix | 19 |
| § 2.3.1 VRT Equation and Its Components | 19 |
| § 2.3.2 Huygen's Principle | 21 |
| § 2.3.3 Optical Theorem and Extinction Coefficient | 23 |
| § 2.4 VRT Equation of Spherical Rayleigh Particles..... | 25 |
| § 2.5 VRT Equation of Spherical Mie Particles..... | 26 |
| § 2.6 VRT Equation of Nonspherical Particles | 28 |
| § 2.6.1 Characteristic Wave Number of Coherent Waves and the Extinction Matrix..... | 28 |
| § 2.6.2 The Phase Matrix of Nonspherical Particles | 31 |
| § 2.7 VRT Equation of Continuous Random Media | 34 |
| § 2.7.1 The Scattering, Extinction Coefficients, and the Phase Matrix | 34 |
| § 2.7.2 Correlation Functions..... | 36 |
| § 2.7.3 Experimental Correlation Length..... | 37 |
| § 2.7.4 Theoretical Discussion on Correlation Length | 40 |
| CHAPTER 3 APPROACHES TO VRT EQUATION AND APPLICATIONS IN PASSIVE AND ACTIVE REMOTE SENSING | 46 |
| § 3.1 Boundary Conditions | 46 |
| § 3.2 Iteration Method for VRT Equation of Spherical Particles | 49 |
| § 3.3 Active Remote Sensing of Atmospheric Precipitation, and Numerical Results | 53 |
| § 3.4 Dielectric Constant of Water, and Other Parameters..... | 61 |
| § 3.4.1 Dielectric Constants of Pure Water, Sea Water, and Ice | 61 |

| | |
|--|------------|
| § 3.4.2 Dielectric Constant of Soil..... | 63 |
| § 3.4.3 Size Distribution of Rain Drops | 66 |
| § 3.4.4 Absorption Coefficient of Atmospheric Gases | 67 |
| § 3.5 Discrete Ordinate and Eigenanalysis Methods | 68 |
| § 3.5.1 Gaussian Quadrature | 68 |
| § 3.5.2 VRT Equation in Discrete Ordinates and the Eigenanalysis Approach | 70 |
| § 3.5.3 Brightness Temperature of Atmospheric Precipitation | 72 |
| § 3.5.4 Mean Permittivity of Vegetation Canopy | 75 |
| § 3.5.5 Brightness Temperature of Vegetation Canopies | 78 |
| § 3.6 Fourier Transformation of VRT Equation of Spherical Particles | 79 |
| § 3.7 Iteration Method of VRT Equation of Nonspherical Particles and Complete Polarimetric Scattering | 87 |
| § 3.7.1 Iteration Method and First-Order Mueller Matrix | 87 |
| § 3.7.2 Complete Polarimetric Scattering and Numerical Results | 90 |
| § 3.7.3 Second-Order Mueller Matrix of Half-Space Model..... | 95 |
| CHAPTER 4 COUPLED VRT EQUATIONS OF MULTI-LAYER MODEL AND TWO-DIMENSIONAL VRT EQUATION..... | 98 |
| §4.1 Coupled VRT equations of Multi-Layers of Random Media | 98 |
| §4.2 Thermal Emission from Stratified, Nonisothermal Atmospheric Precipitation | 100 |
| §4.3 Thermal Emission from a Multi-Layers Model with Vertical Structure for Forest | 104 |
| §4.4 Two-Dimensional VRT Equation of a Layer of Nonuniform Random Medium | 109 |
| §4.4.1 Fourier Transformation in Discrete Form..... | 109 |
| §4.4.2 Iteration Solutions | 111 |
| §4.5 Numerical Solutions of Two-Dimensional VRT Equation | 113 |
| CHAPTER 5 ANALYTIC WAVE THEORY OF RANDOM MEDIA..... | 118 |
| § 5.1 Dyadic Green's Function (DGF) of Stratified Media | 118 |
| § 5.1.1 Fourier Expansion of DGF of Infinite Free Space..... | 118 |
| § 5.1.2 Fourier Expansion of DGF of Stratified Media | 120 |
| § 5.1.3 Stationary Phase Method and DGF in the Far Field Approximation | 123 |
| § 5.2 Backscattering Coefficient in First-Order Born Approximation | 124 |
| § 5.3 Backscattering Coefficient of Multi-layer Random Media | 131 |
| § 5.4 Weak Fluctuation Condition for the Effective Dielectric Constant of Random Media | 132 |
| § 5.5 Fluctuation Dissipation Theorem and WKB Solution..... | 134 |
| § 5.5.1 Brightness Temperature of Stratified Dissipative Media | 134 |
| § 5.5.2 WKB Solution..... | 136 |
| § 5.5.3 Brightness Temperature of Soil with Continuous Temperature and Moisture Profiles..... | 139 |
| § 5.6 Renormalization of Wave Equation and Feynman Diagram | 143 |
| § 5.6.1 Secular Term in the Second-Order Solution of Coherent Field..... | 143 |

| | | |
|------------------|--|------------|
| § 5.6.2 | Dyson Equation and Approximation | 144 |
| § 5.6.3 | Bether-Salpeter Equation and Approximation..... | 149 |
| CHAPTER 6 | STRONG FLUCTUATION THEORY..... | 154 |
| § 6.1 | Scattering of a Layer of Strongly Fluctuating Random Medium..... | 154 |
| § 6.1.1 | Scattering Intensity under Distorted Born Approximation..... | 154 |
| § 6.1.2 | Effective Permittivity and Explanation of s - ξ transform | 157 |
| § 6.1.3 | Correlation Function of Discrete Scatterers..... | 160 |
| § 6.2 | Bistatic and Backscattering Coefficients | 161 |
| § 6.3 | Second-Order Depolarized Backscattering | 166 |
| Appendix A6-1 | $\bar{E}_{01}^{\pm}(\vec{k}_p, \vec{x}, \vec{x}_1)$, $\bar{E}_{11}^{\pm}(\vec{k}_p, \vec{x}_1, \vec{x}_2)$, and $\bar{F}_m(\vec{x})$ | 171 |
| Appendix A6-2 | $A_{20}^{\pm}(\phi)_{s,s',p,p'}$ and $A_{0h}^{\pm}(\phi)_{s,s',p,p'}$ | 172 |
| Appendix A6-3 | Some Relations..... | 174 |
| § 6.4 | Application of the Fluctuation Dissipation Theorem in Strongly Fluctuated Random Media | 174 |
| § 6.4.1 | Zeroth- and First-Order Brightness Temperatures | 175 |
| § 6.4.2 | Numerical Results and Discussion | 179 |
| Appendix B6-1 | C_{mn} , H_n , V_n and U_n | 182 |
| § 6.5 | VRT Equation of Strongly Fluctuating, Nonisotropic, Continuous Random Media..... | 183 |
| § 6.5.1 | The Phase Matrix | 184 |
| § 6.5.2 | Coefficient of δ Function in DGF | 187 |
| § 6.6 | Dielectric Constant of Sea Ice..... | 190 |
| § 6.7 | VRT Numerical Results of Brightness Temperature of Snowpack and Sea Ice | 194 |
| § 6.8 | Second-Order Bistatic Scattering and Backscattering Enhancement | 198 |
| Appendix C6-1 | $A_{2h}^{\pm}(\phi)_{s,s',p,p'}$ and $A_{0v}^{\pm}(\phi)_{s,s',p,p'}$ | 206 |
| Appendix C6-2 | $D_{hh}^{\pm}(\phi)_{s,s',p,p'}$ | 210 |
| Appendix C6-3 | C_{mn}^* | 212 |
| CHAPTER 7 | RADIATIVE TRANSFER OF DENSELY DISTRIBUTED, RANDOM DISCRETE SCATTERERS (DVRT) | 214 |
| § 7.1 | Pair Distribution Function | 214 |
| § 7.2 | Effective Propagation Constant Under Quasicrystalline Approximation with Coherent Potential (QCA-CP)..... | 216 |
| § 7.3 | Energy Consistency of QCA-CP and the Ladder Approximations..... | 222 |
| § 7.4 | DVRT Equation of a Layer of Densely Distributed, Random Discrete Scatterers | 223 |
| Appendix A7-1 | \bar{P} and J_m in DVRT Equation | 229 |
| § 7.5 | Iteration Solution and Constructive Interference..... | 230 |
| § 7.6 | Numerical Results of Thermal DVRT Equation | 235 |
| § 7.7 | Improvement of the RADTRAN Code..... | 238 |
| CHAPTER 8 | SCATTERING FROM RANDOM ROUGH SURFACE | 243 |
| § 8.1 | The Kirchhoff Approximation (KA) | 244 |

| | | |
|------------------|---|-----|
| § 8.1.1 | KA Tangent Plane Approximation and Solution of Geometric Optics | 244 |
| § 8.1.2 | KA Solution of Quasi-Periodic Random Rough Surface..... | 250 |
| § 8.1.3 | KA Solution of Skewed Random Rough Surface..... | 254 |
| § 8.1.4 | Shadowing Function | 256 |
| § 8.2 | Small Perturbation Approximation (SPA) and Two Scale Model..... | 260 |
| § 8.2.1 | Small Perturbation Solution..... | 260 |
| § 8.2.2 | Scattering from Two-Scale Random Rough Surface..... | 262 |
| § 8.2.3 | Sea Spectrum | 267 |
| § 8.2.4 | Numerical Results of Scattering from Rough Sea Surface..... | 270 |
| § 8.3 | Iteration Solution of VRT Equation with Randomly Rough Surface | 273 |
| § 8.4 | Second-Order Scattering and Backscattering Enhancement..... | 277 |
| § 8.4.1 | Second-Order Scattering..... | 277 |
| § 8.4.2 | Angular Backscattering Enhancement | 282 |
| | Appendix A8-1 $F_{pq}^{(z+)}$, $F_{pq}^{(1+)}$, $F_{pq}^{(z-)}$, and $F_{pq}^{(1-)}$ | 286 |
| REFERENCES | | 287 |

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

$$\vec{E}_i(\vec{r}) = (\partial_i E_{i_0} + \hat{h}_i \cdot \vec{E}_{i_0}) e^{i\hat{k}_i \cdot \vec{r}} \equiv \partial_i E_{i_0} e^{i\hat{k}_i \cdot \vec{r}} \quad (1.1)$$

入射在介电常数 ϵ ，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

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

水平 (TE 波) 和垂直 (TM 波) 极化矢量分别定义为

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

$$\hat{o} = \hat{h} \times \hat{k} = \hat{x} \cos \theta \cos \phi + \hat{y} \cos \theta \sin \phi - \hat{z} \sin \theta \quad (1.2c)$$

可看出，若用球坐标 (ρ, θ, ϕ) 来表示，则

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

我们有 Maxwell 方程为

$$\nabla \times \vec{E} = i\omega\mu\vec{H} \quad (1.3a)$$

$$\nabla \times \vec{H} = -i\omega\epsilon[\epsilon_{,n}(\vec{r}) - 1]\vec{E} - i\omega\epsilon\vec{E} \quad (1.3b)$$

其中 $\epsilon_{,n}(\vec{r}) = \epsilon_s(\vec{r})/\epsilon$ ，下标 n 为归一化。方程 (1.3b) 中 $-i\omega\epsilon[\epsilon_{,n}(\vec{r}) - 1]$ 看作是

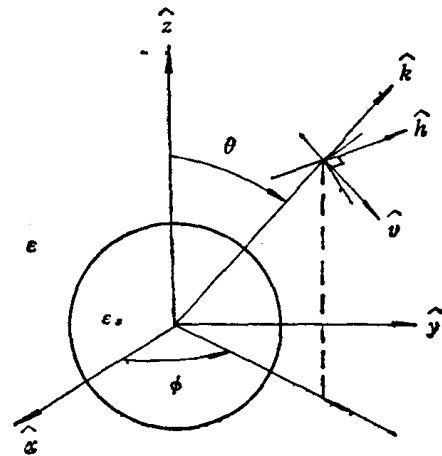


图 1.1 入射波和极化矢量