

ATMOSPHERIC LIDAR FUNDAMENTALS

Laser Light Scattering from Atoms and Linear Molecules

Lidar is a remote sensing technique that employs laser beams to produce a high-resolution, four-dimensional probe, with important applications in atmospheric science. Suitable as a detailed reference or an advanced textbook for interdisciplinary courses, this book discusses the underlying principles of light-scattering theory and describes widely used lidar systems in current research, exploring how they can be employed effectively for atmospheric profiling. This self-contained text provides a solid grounding in the essential physics of light-matter interactions and the fundamentals of atmospheric lidars through a discussion of the principles that govern light-matter interactions and an exploration of both historical and recent scientific developments in lidar technology. This is an essential resource for physicists, optical engineers, and other researchers in atmospheric science and remote sensing.

CHIAO-YAO SHE is Emeritus Professor of Physics at Colorado State University and a Fellow of the Optical Society of America. Dr. She earned his Ph.D. from Stanford University in 1964. He has decades of experience in areas of laser light scattering spectroscopy and atmospheric lidar that enabled important scientific investigations. He also pioneered two narrowband atmospheric lidars that have been duplicated internationally for atmospheric research and observations. He has an outstanding research and publication record including more than two hundred papers on related topics and two book chapters.

JONATHAN S. FRIEDMAN received his Ph.D. from Colorado State University in 1991 and is currently the Director of the Puerto Rico Photonics Institute, which he founded in 2011 at the Universidad Ana G. Mendez. For twenty-six years, he was a research associate at the Arecibo Observatory for Cornell University, and at SRI International. In addition to developing and employing lidar technology to study the atmosphere, he has also published extensively in the field of lidar science and spectroscopic physics.

Cambridge University Press
978-1-316-51823-6 — Atmospheric Lidar Fundamentals
Chiao-Yao She , Jonathan S. Friedman
Frontmatter
[More Information](#)

ATMOSPHERIC LIDAR FUNDAMENTALS

Laser Light Scattering from Atoms and Linear Molecules

CHIAO-YAO SHE

Colorado State University

JONATHAN S. FRIEDMAN

Ana G. Mendez University



CAMBRIDGE
UNIVERSITY PRESS

Cambridge University Press
978-1-316-51823-6 — Atmospheric Lidar Fundamentals
Chiao-Yao She, Jonathan S. Friedman
Frontmatter
[More Information](#)

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom
One Liberty Plaza, 20th Floor, New York, NY 10006, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India
103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of the University of Cambridge.
It furthers the University's mission by disseminating knowledge in the pursuit of
education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781316518236
DOI: 10.1017/9781108968713

© Chiao-Yao She and Jonathan S. Friedman 2022

This publication is in copyright. Subject to statutory exception
and to the provisions of relevant collective licensing agreements,
no reproduction of any part may take place without the written
permission of Cambridge University Press.

First published 2022

A catalogue record for this publication is available from the British Library.

ISBN 978-1-316-51823-6 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of
URLs for external or third-party internet websites referred to in this publication
and does not guarantee that any content on such websites is, or will remain,
accurate or appropriate.

Cambridge University Press
978-1-316-51823-6 — Atmospheric Lidar Fundamentals
Chiao-Yao She , Jonathan S. Friedman
Frontmatter
[More Information](#)

To
Lucy, Colleen, and Camille
Ivonne, Coralie, Bart, and Sheila

Cambridge University Press
978-1-316-51823-6 — Atmospheric Lidar Fundamentals
Chiao-Yao She , Jonathan S. Friedman
Frontmatter
[More Information](#)

Contents

<i>Foreword by Dr. John L. “Jan” Hall</i>	<i>page xi</i>
<i>Preface</i>	<i>xiii</i>
1 Introduction	1
References	6
2 Classical Light Scattering Theory	7
2.1 A Simple Model of Atomic Polarizability and Differential Scattering Cross Section	8
2.2 Resonant and Nonresonant Scattering from the Atmosphere	11
2.3 Physical Causes of Broadened Light Scattering Spectra	14
References	16
3 Semiclassical Treatment of Light Absorption and Scattering from Atoms	17
3.1 Doppler Shift in Backscattering: Nonresonant versus Resonant Processes	17
3.2 Quantum Polarizability and Absorption Cross Section	20
3.3 Differential Resonance Scattering Cross Sections	24
3.4 Application to Real Atoms with Interest to Atmospheric Lidars	31
3.5 Rudimentary Physics of Na Laser Guide Stars	40
References	48
4 Rayleigh and Raman Scattering from Linear Molecules	50
4.1 Formulation and Evaluation of Polarizability Tensor	52
4.2 Differential Light Scattering Cross Section from an Ensemble of Linear Molecules	58
	vii

4.3	Rayleigh and Vibrational Raman Spectra of Nitrogen and Oxygen Molecules	72
4.4	Cabannes Scattering Spectra	83
	References	92
5	Introduction to Lidar Remote Sensing and the Lidar Equation	94
5.1	The Lidar Equation – An Overview	99
	References	102
6	Common (Broadband) Lidar Types and Associated Applications	103
6.1	Rayleigh–Mie Scattering (Elastic Backscattering) Lidars	103
6.2	Polarization Lidars	111
6.3	Raman Lidar and DIAL for Monitoring Minor Species in the Atmosphere	121
6.4	Other Important Lidar Types Not Discussed in This Book	131
	References	134
7	Lidars for Profiling Aerosol Optical Properties, Atmospheric Temperature and Wind	138
7.1	Profiling Lidar-Ratio and Aerosol Optical Properties	142
7.2	Temperature Measurements with Rayleigh and Rotational Raman Scattering	150
7.3	HSRL Profiling of Aerosol Optical Properties and Atmospheric State Parameters	166
7.4	Wind Profiling with Cabannes-Mie Scattering	194
7.5	Mesopause Region Temperature and Wind Profiling with LIF	209
	References	236
8	Transmitting and Receiving Optics	244
8.1	Conservation of Étendue in Transmission and Reception Optics	244
8.2	Laser Beam Expander and Its Use	246
8.3	Telescope Optics	249
8.4	Detectors	256
8.5	The Effects of Atmospheric Turbulence on Receiver Aperture and Na Laser Guide Star	261
	References	267
	<i>Appendix A: Electric Dipole Interaction and Structures of Atoms and Linear Molecules</i>	268

<i>Contents</i>	ix
A.1 Basics of the Electric Dipole Transition	270
A.2 Energy Structure of Na, K, and Fe Atoms and of Nd ³⁺ , Cr ³⁺ in Crystals	275
A.3 Structure of Linear Molecules	287
A.4 A Brief Account of Thermodynamics and Transport of an Ideal Molecular Gas	299
References	301
<i>Appendix B: Coordinate Systems and Mueller Matrices</i>	303
B.1 Rotation of an Object and Transformation of Coordinate Systems	304
B.2 Rotations in Three-Dimensional Space and Euler Angles	305
B.3 Specification of Selected Sets of Unit Vectors Associated with Finite Rotations	307
B.4 Atoms in the Earth’s Magnetic Field	307
B.5 Jones Vectors, Jones Matrices, and Nondepolarizing Optical Devices	309
B.6 Stokes Vectors, Mueller Matrices, and Atmospheric Scattering	309
References	312
<i>Appendix C: Chiao-Yao She’s Research Career at Colorado State University: An Autobiographical Acknowledgment</i>	313
<i>Index</i>	318

Cambridge University Press
978-1-316-51823-6 — Atmospheric Lidar Fundamentals
Chiao-Yao She , Jonathan S. Friedman
Frontmatter
[More Information](#)

Foreword

In studying the several chapter drafts, I can see that this book will be a valuable addition to the literature, especially in that the historical evolution of the field of atmospheric lidar is so nicely laid out. This is hardly surprising, as the author, Professor Chiao-Yao She (formerly of the Colorado State University in Fort Collins, Colorado), has been a pioneer in the field over the decades. Importantly, the book also covers recent advances in atmospheric lidars from selected literature between 2005 and 2021, not contained in previous books of this type. Additionally, there is ample material to get the new researcher “up to speed” in the latest topics, such as the laser guide star idea and approaches.

One fundamental issue is the dynamic range requirements that must be met for any real success in this atmospheric lidar business: the transmitted pulses are measured in joules, while the returns are measurable as time-dispersed single photon detection events. These signal scales are separated by the (detection) sensitivity factor $\sim 10^{19}$, which is attenuation incurred in these experiments thanks to the unfavorable geometrical factors. While we have all experienced some “dark days” when sunlight is diminished by clouds and raindrops scatter sunlight before it arrives to warm us, this attenuation factor is rarely more than $30\times$, not the 10^{19} -fold encountered in upper atmospheric lidar. On the other hand, we know that nearby scattered outbound laser light will be far too intense for the sensitive receivers. A first idea is to use the time delay of the interesting echo, since it is (just) possible to design detectors that have fast-enough recovery from overload.

Another and more powerful approach is to use notch-like narrowband spectral filters in the return detection system, as light scattered by dust and aerosols will be substantially unchanged in wavelength. But atmospheric molecules have their own frequency shifts resulting from different modes of motion, so the receiver can be off-tuned the proper amount to receive the shifted light and mostly block the transmitter’s pulse. But to get deep-enough absorption of the scattered primary beam is not trivial, so the community was glad to have molecules such as iodine, which offer strong absorption bands near 532 nm, the wavelength of powerful frequency-doubled Nd-YAG pulse lasers. Under proper conditions these absorbing cells can be essentially transparent for the desired, shifted wavelengths resulting from Cabannes, pure rotational Raman, and vibrational Raman scattering, corresponding to their (random) translational, rotational, and vibrational motions respectively. In the upper atmosphere, where aerosol scattering is not a concern, the community uses very

narrowband Fabry–Perot étalon (narrower than 2 GHz) and Faraday filters to diminish skylight background.

I was particularly rewarded by the author’s historical coverage of the LIDAR science and technology. Professor She introduced atomic and molecular (iodine) filters to the tropospheric lidar community in 1983. After hearing of the atmospheric Na layer in 1987, he and his students developed Na laser–induced fluorescence lidar in 1989, then pioneered atmospheric temperature measurements in the sodium layer near 90 km, at the border between the atmosphere and space, studying gravity waves, tides, and secular (long-term) changes. His group continually advanced the technology, adding dual two-pass acousto-optic modulators to enable atmospheric wind measurement, Na vapor Faraday filters for daylight measurement, and sum-frequency generation to reach 589 nm as an attempt to improve the lidar transmitter. Most of these contributions can be found in Chapter 7. This book includes stories about how his group got the first results; for example, the excitement of receiving Na signal in 2000 for the first time in Arctic Norway under 24-hour daylight. As the reader may know, this reflected light from the 90-km-altitude Na layer is now routinely used to represent a “point-source” of astronomical light. Its return image is used to dynamically adjust the multi-segment optics of many modern telescopes to largely remove the degrading of obtained images by atmospheric scintillation and shearing.

For this reader, Section 8.5 is delicious – it incorporates some analysis of signal levels and expected turbulence scaling, but the presentation about the LGS work is the home run. I had known about and even visited Roger Angel’s rotating furnace for making large parabolic mirror blanks. But I didn’t know the where and who about the guide-star development. It looks like Mr Fugate’s Albuquerque team is one of the main heroes.

This book project seems to have morphed from a history of stuff that happened and new lidars that were developed, with many interesting observations and results, into a book for every optics student to enjoy and be inspired by. I was astonished to find a reference to the Fugate lecture on YouTube. Perhaps there is some public information about one of the current frontier telescopes (Hawaii and/or Chile), where this spin-off from the field’s work is leading to applications in astronomy.

Also, I wonder if there is something interesting about atmospheric chemistry that could be diagnosed using the spatial resolution possibilities. Would that occur only if the reactions had a nonlinear density dependence?

Professor She and his coauthor have been active for decades in training researchers in the atmospheric LIDAR business. His research program had its home base in Colorado, with many Ph.D.-level researchers being educated in the LIDAR arts. He also was involved in many collaborations at other labs at geophysically interesting places, such as northern Norway. Such experiences for students definitely will involve broad learning not usually available in a regular course of study. You will like this book.

Dr. John L. “Jan” Hall
Senior Fellow of NIST, Emeritus
Adjoint Professor of Physics, University of Colorado
Nobel Laureate in Physics 2005

Preface

As its title, *Atmospheric Lidar Fundamentals: Laser Light Scattering from Atoms and Linear Molecules*, suggests, this book treats the fundamentals of atmospheric lidar from first physics principles. The introductory chapter gives a brief description of the relation between the optical processes involved and atmospheric lidars. The relevant optical processes are first discussed classically in Chapter 2. Supplemented by Appendix A, Chapter 3 discusses the processes of light absorption, scattering, and laser-induced fluorescence (LIF) for atomic systems. Here, we employ semiclassical (quantum) theory along with spectroscopy of atoms relevant to atmospheric lidar and Na laser guide stars (LGS). This is followed in Chapter 4 by quasi-elastic (Rayleigh) and inelastic (Raman) laser light scattering from linear molecules. Utilizing the results developed in Chapters 2–4, we use the following three chapters to discuss atmospheric lidars: in Chapter 5, the lidar equation; in Chapter 6, lidars using broadband pulsed lasers, including Rayleigh–Mie, and conventional and Stokes-vector-based polarization lidars; and in Chapter 7, lidars using narrowband pulsed lasers for the measurement of aerosol optical properties and atmospheric state parameters (density, temperature, and wind) via Cabannes scattering, pure rotational Raman scattering, and laser-induced fluorescence. Finally, in Chapter 8 we give an overview of transmitting and receiving optics and telescopes along with a brief account on atmospheric turbulence and Laser Guide Star (LGS) for ground-based astronomical telescopes.

The monograph is written in a textbook format. As such, it follows, as is typical, a logical order of information dissemination, starting with an introduction, followed by basic principles and then applications. If the research career of one author (CYS) of this book (briefly described in Appendix C) might inspire many scientists interested in applications, the chronology of events is less orderly than one might anticipate. Such an evolution often begins with a practical problem requiring a creative solution. This is followed by one or more ideas and preferably, if possible, some preliminary investigations. Following the good fortune to secure

funding, integration of a team of graduate students in a university project leads to mining the often scattered and difficult literature and, ultimately, to deeper understanding of the associated basics. In the process, dissertations are written and advanced degrees are awarded. With luck, this deeper basic understanding inspires more exciting methods for solving deeper and broader basic and applied problems. This is our roundabout way of stating our strong belief that, in addition to necessary and timely technology, a sound physical understanding of the basics and quantitative knowledge of various light scattering processes will enhance the creativity of students and researchers in the field of laser remote sensing, or LIDAR (**L**ight **D**etection **A**nd **R**anging). Our limited experience in working with young students and researchers in applied sciences worldwide has led us to know that they are typically highly motivated to succeed, and, thanks to the Internet, they are increasingly skilled at computer programming and knowledgeable about openly available technical information. At the same time, they are generally less proficient with relevant basic physics principles and historical developments. A common element is that their lives are a lot busier than those of their counterparts decades ago. Our motivation for this book is then primarily to support these lovely young researchers by presenting a concise, single source for the principles of relevant optical processes coupled with showcase examples of modern atmospheric lidars.

This is an interdisciplinary book in the field of applied optics, overlapping the disciplines of atmospheric lidars and optical spectroscopy. It is intended for advanced undergraduate and graduate students in physics, chemistry, optical engineering, and atmospheric sciences, as well as researchers in research institutes and optics industries who develop and/or use lidars for remote sensing and atmospheric studies. The book could be a text or major reference for an interdisciplinary special topics-type course for advanced undergraduate and graduate students in a physics or atmospheric sciences department. It could also be a text for a semester course at the same level in light scattering and spectroscopy of atoms and simple molecules in departments of physics, chemistry, or optical engineering. Such a course, though it may be considered old fashioned nowadays, is in our view very useful for the scientific well-being of most students; it may be constructed from the materials in Chapters 1–4 along with Appendices A and B. This text could also be used for a course in atmospheric lidars in engineering or atmospheric/environmental sciences, in which case the course would most benefit from the materials in Chapters 1, 5, 6, 7, and 8 along with Appendix B.

We acknowledge the contributions of our many research collaborators, colleagues, visitors, and graduate students, too numerous to name here (see Appendix C), who have sustained and stimulated our learning process and have directly or indirectly influenced the writing of this book and the content therein. We are grateful for many

Preface

xv

discussions with Jay Yu on the coherent detection technique for wind measurement, and with Raul Alvarez, John Hair, and Dave Krueger on Cabannes scattering and associated temperature measurements, which we pursued more than two decades ago. We thank Chet Gardner for suggesting the inclusion of a brief discussion on laser guide stars, and Paul Hickson for providing relevant expert references on this exciting development. We also thank Jan Hall, who kindly authored the foreword to this book and made suggestions to improve the presentation of Chapter 7 while reading draft chapters. We are deeply grateful for the assistance of Zhao-Ai Yan, who prepared all the figure presentations for this book. JSF gratefully acknowledges the patient mentorship and leadership of the late Craig Tepley, who transformed him from a crude postdoc to a more accomplished researcher.

Cambridge University Press
978-1-316-51823-6 — Atmospheric Lidar Fundamentals
Chiao-Yao She , Jonathan S. Friedman
Frontmatter
[More Information](#)
