ELASTIC LIDAR
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It has been 20 years since the last comprehensive book on the subject of lidars was written by Raymond Measures. In that time, technology has come a long way, enabling many new capabilities, so much so that cataloging all of the advances would occupy several volumes. We have limited ourselves, generally, to elastic lidars and their function and capabilities. Elastic lidars are, by far, the most common type of lidar in the world today, and this will continue to be true for the foreseeable future. Elastic lidars are increasingly used by researchers in fields other than lidar, most notably by atmospheric scientists. As the technology moves from being the point of the research to providing data for other types of researchers to use, it becomes important to have a handbook that explains the topic simply, yet thoroughly. Our goal is to provide elastic lidar users with simple explanations of lidar technology, how it works, data inversion techniques, and how to extract information from the data the lidars provide. It is our hope that the explanations are clear enough for users in fields other than physics to understand the device and be capable of using the data productively. Yet we hope that experienced lidar researchers will find the book to be a useful handbook and a source of ideas.

Over the 40 years since the invention of the laser, optical and electronic technology has made great advances, enabling the practical use of lidar in many fields. Lidar has indeed proven itself to be a useful tool for work in the atmosphere. However, despite the time and effort invested and the advances that have been made, it has never reached its full potential. There are two basic reasons for this situation. First, lidars are expensive and complex instruments that require trained personnel to operate and maintain them. The second reason is related to the inversion and analysis of lidar data. Historically, most
lidars have been research instruments for which the focus has been on the development of the instrument as opposed to the use of the instrument. In recent years, the technology used in lidars has become cheaper, more common, and less complex. This has reduced the cost of such systems, particularly elastic lidars, and enabled their use by researchers in fields other than lidar instrument development.

The problem of the analysis of lidar data is related to problems of lidar signal interpretation. Despite the wide variety of the lidar systems developed for periodical and routine atmospheric measurements, no widely accepted method of lidar data inversion or analysis has been developed or adopted. A researcher interested in the practical application of lidars soon learns the following: (1) no standard analysis method exists that can be used even for the simplest lidar measurements; (2) in the technical literature, only scattered practical recommendations can be found concerning the derivation of useful information from lidar measurements; (3) lidar data processing is, generally, considered an art rather than a routine procedure; and (4) the quality of the inverted lidar data depends dramatically on the experience and skill of the researcher.

We assert that the widespread adoption of lidars for routine measurements is unlikely until the lidar community can develop and adopt inversion methods that can be used by non-lidar researchers and, preferably, in an automated fashion. It is difficult for non-lidar researchers to orient themselves in the vast literature of lidar techniques and methods that have been published over the last 20–25 years. Experienced lidar specialists know quite well that the published lidar studies can be divided into two unequal groups. The first group, the smaller of the two groups, includes some useful and practical methods. In the other group, the studies are the result of good intentions but are often poorly grounded. These ideas either have not been used or have failed during attempts to apply them. In this book, we have tried to assist the reader by separating out the most useful information that can be most effectively applied. We attempt to give readers an understanding of practical data processing methodologies for elastic lidar signals and an honest explanation of what lidar can do and what it cannot do with the methods currently available. The recommendations in the book are based on the experience of the authors, so that the viewpoints presented here may be arguable. In such cases, we have attempted to at least state the alternative point of view so that reader can draw his or her own conclusions. We welcome discussion.

The book is intended for the users of lidars, particularly those that are not lidar instrument researchers. It should also serve well as a useful reference book for remote sensing researchers. An attempt was made to make the book self-contained as much as possible. Inasmuch as lidars are used to measure constituents of the earth’s atmosphere, we begin the book in Chapter 1 by covering the processes that are being measured. The light that lidars measure is scattered from molecules and particulates in the atmosphere. These processes are discussed in Chapter 2. Lidars use this light to measure optical properties
of particulates or molecules in the air or the properties of the air (temperature or optical transmission, for example). Chapter 3 introduces the reader to lidar hardware and measurement techniques, describes existing lidar types, and explains the basic lidar equation, relating lidar return signals to the atmospheric characteristics along the lidar line of sight. In Chapter 4, the reader is briefly introduced to the electronics used in lidars. Chapter 5 deals with the basic analytical solutions of the lidar equation for single- and two-component atmospheres. The most important sources of measurement errors for different solutions are analyzed in Chapter 6. Chapter 7 deals with the fundamental problem that makes the inversion of elastic lidar data difficult. This is the uncertainty of the relationship between the total scattering and backscattering for atmospheric particulates. In Chapter 8, methods are considered for one-directional lidar profiling in clear and moderately turbid atmospheres. In addition, problems associated with lidar measurement in “spotted” atmospheres are included. Chapter 9 examines the basic methods of multiangle measurements of the extinction coefficients in clear atmospheres. The differential absorption lidar (DIAL) processing technique is analyzed in detail in Chapter 10. In Chapter 11, hardware solutions to the inversion problem are presented. A detailed review of data analysis methods is given in Chapters 12 and 13. Despite an enormous amount of literature on the subject, we have attempted to be inclusive. There will certainly be methods that have been overlooked.

We wish to acknowledge the assistance of the Iowa Institute for Hydraulic Research for making this book possible. We are also deeply indebted to the work that Bill Grant has done over the years in maintaining an extensive lidar bibliography and to the many people who have reviewed portions of this book.

Vladimir A. Kovalev
William E. Eichinger
DEFINITIONS

$\beta_{n,m}$ Molecular angular scattering coefficient in the direction $\theta = 180^\circ$, relative to the direction of the emitted light (m$^{-1}$ steradian$^{-1}$)

$\beta_{n,p}$ Particulate angular scattering coefficient in the direction $\theta = 180^\circ$ relative to the direction of the emitted light (m$^{-1}$ steradian$^{-1}$)

$\beta_{n,R}$ Raman angular scattering coefficient in the direction $\theta = 180^\circ$ relative to the direction of the emitted light

$\beta_n = \beta_{n,p} + \beta_{n,m}$ Total of the molecular and particulate angular scattering coefficients in the direction $\theta = 180^\circ$

$\beta_m$ Molecular scattering coefficient (m$^{-1}$, km$^{-1}$)

$\beta_p$ Particulate scattering coefficient (m$^{-1}$, km$^{-1}$)

$\beta$ Total (molecular and particulate) scattering coefficient, $\beta = \beta_m + \beta_p$

$\Delta \sigma = \sigma_{on} - \sigma_{off}$ Differential absorption cross section of the measured gas

$\kappa_{A,m}$ Molecular absorption coefficient

$\kappa_{A,p}$ Particulate absorption coefficient

$\kappa_A$ Total (molecular and particulate) absorption coefficient, $\kappa_A = \kappa_{A,m} + \kappa_{A,p}$

$\kappa_m$ Total (scattering + absorption) molecular extinction coefficient, $\kappa_m = \beta_m + \kappa_{A,m}$

$\kappa_p$ Total (scattering + absorption) particulate extinction coefficient, $\kappa_p = \beta_p + \kappa_{A,p}$

$\kappa_t$ Total (molecular and particulate) extinction coefficient, $\kappa_t = \kappa_p + \kappa_m$

$\lambda$ Wavelength of the radiant flux

$\lambda_d$ Wavelength of the laser emission

$\lambda_{off}$ Wavelength of the off-line DIAL signal
\( \lambda_{on} \) Wavelength of the on-line DIAL signal
\( \lambda_R \) Wavelength of the Raman shifted signal
\( \Pi_m \) Molecular backscatter-to-extinction ratio, \( \Pi_m = \beta_{n,m}/(\beta_m + \kappa_{A,m}) \) (steradian\(^{-1}\))
\( \Pi_p \) Particulate backscatter-to-extinction ratio, \( \Pi_p = \beta_{n,p}/(\beta_p + \kappa_{A,p}) \) (steradian\(^{-1}\))
\( \sigma_{0,p} \) Particulate angular scattering cross section
\( \sigma_{N_2} \) Nitrogen Raman cross section (m\(^2\))
\( \sigma_{s,p} \) Particle scattering cross section
\( \sigma_{s,m} \) Molecular scattering cross section
\( \sigma_{t,p} \) Particulate total (extinction) cross section (m\(^2\))
\( \sigma_{t,m} \) Molecular total cross-section (m\(^2\))
\( \tau(r_1,r_2) \) Optical depth of the range from \( r_1 \) to \( r_2 \) in the atmosphere
\( h \) Height
\( n_m \) Molecular density (number/m\(^3\))
\( P(r, \lambda) \) Power of the lidar signal at wavelength \( \lambda \) created by the radiant flux backscattered from range \( r \) from lidar with no range correction
\( P_{\pi,p} \) Particulate backscatter phase function, \( P_{\pi,p} = \beta_{n,p}/\beta_p \) (steradian\(^{-1}\))
\( P_{\pi,m} \) Molecular backscatter phase function, \( P_{\pi,m} = \beta_{n,m}/\beta_m = 3/8\Pi \) (steradian\(^{-1}\))
\( r_0 \) Minimum lidar measurement range
\( r_{max} \) Maximum lidar measurement range
\( Z(r) = P(r) r^2 Y(r) \) Lidar signal transformed for the inversion
\( Z_r(r) \) Range-corrected lidar return
\( T(r_1, r_2) \) One-way atmospheric transmittance of layer \( (r_j, r_2) \)
\( T_0 \) One-way atmospheric transmittance from the lidar \( (r = 0) \) to the system minimum range \( r_0 \) as determined by incomplete overlap
\( T_{max} = T(r_0, r_{max}) \) One-way atmospheric transmittance for the maximum lidar range, from \( r_0 \) to \( r_{max} \)
\( u \) Angstrom coefficient
\( Y(r) \) Lidar signal transformation function
It is our intention to provide in this chapter some basic information on the atmosphere that may be useful as a quick reference for lidar users and suggestions for references for further information. Many of the topics covered here have books dedicated to them. A wide variety of texts are available on the composition and structure, physics, and chemistry of the atmosphere that should be used for detailed study.

1.1. ATMOSPHERIC STRUCTURE

1.1.1. Atmospheric Layers

The atmosphere is a relatively thin gaseous layer surrounding the earth; 99% of the mass of the atmosphere is contained in the lowest 30km. Table 1.1 is a list of the major gases that comprise the atmosphere and their average concentration in parts per million (ppm) and in micrograms per cubic meter. Because of the enormous mass of the atmosphere \((5 \times 10^{18} \text{kg})\), which includes a large amount of water vapor, and its latent heat of evaporation, the amount of energy stored in the atmosphere is large. The mixing and transport of this energy across the earth are in part responsible for the relatively uniform temperatures across the earth’s surface.

There are five main layers within the atmosphere (see Fig. 1.1). They are,
TABLE 1.1. Gaseous Composition of Unpolluted Wet Air

<table>
<thead>
<tr>
<th></th>
<th>Concentration, ppm</th>
<th>Concentration, µg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>756,500</td>
<td>8.67 × 10⁸</td>
</tr>
<tr>
<td>Oxygen</td>
<td>202,900</td>
<td>2.65 × 10⁸</td>
</tr>
<tr>
<td>Water</td>
<td>31,200</td>
<td>2.30 × 10⁷</td>
</tr>
<tr>
<td>Argon</td>
<td>9,000</td>
<td>1.47 × 10⁷</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>305</td>
<td>5.49 × 10⁴</td>
</tr>
<tr>
<td>Neon</td>
<td>17.4</td>
<td>1.44 × 10⁴</td>
</tr>
<tr>
<td>Helium</td>
<td>5.0</td>
<td>8.25 × 10²</td>
</tr>
<tr>
<td>Methane</td>
<td>1.16</td>
<td>7.63 × 10¹</td>
</tr>
<tr>
<td>Krypton</td>
<td>0.97</td>
<td>3.32 × 10³</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>0.49</td>
<td>8.73 × 10²</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.49</td>
<td>4.00 × 10¹</td>
</tr>
<tr>
<td>Xenon</td>
<td>0.08</td>
<td>4.17 × 10²</td>
</tr>
<tr>
<td>Organic vapors</td>
<td>0.02</td>
<td>—</td>
</tr>
</tbody>
</table>

Bouble et al. (1994).

Fig. 1.1. The various layers in the atmosphere of importance to lidar researchers.

from top to bottom, the exosphere, the thermosphere, the mesosphere, the stratosphere, and the troposphere. Within the troposphere, the planetary boundary layer (PBL) is an important sublayer. The PBL is that part of the atmosphere which is directly affected by interaction with the surface.
Exosphere. The exosphere is that part of the atmosphere farthest from the surface, where molecules from the atmosphere can overcome the pull of gravity and escape into outer space. The molecules of the atmosphere diffuse slowly into the void of space. The lower limit of the exosphere is usually taken as 500 km, but there is no definable boundary to mark the end of the thermosphere below and the beginning of the exosphere. Also, there is no definite top to the exosphere: Even at heights of 800 km, the atmosphere is still measurable. However, the molecular concentrations here are very small and are considered negligible.

Thermosphere. The thermosphere is a relatively warm layer above the mesosphere and just below the exosphere. In this layer, there is a significant temperature inversion. The few atoms that are present in the thermosphere (primarily oxygen) absorb ultraviolet (UV) energy from the sun, causing the layer to warm. Although the temperatures in this layer can exceed 500 K, little total energy is stored in this layer. Unlike the boundaries between other layers of the atmosphere, there is no well-defined boundary between the thermosphere and the exosphere (i.e., there is no boundary known as the thermopause). In the thermosphere and exosphere, molecular diffusion is the dominant mixing mechanism. Because the rate of diffusion is a function of molecular weight, separation of the molecular species occurs in these layers. In the layers below, turbulent mixing dominates so that the various molecular species are well mixed.

Mesosphere. The mesosphere is the middle layer in the atmosphere (hence, mesosphere). The temperature in the mesosphere decreases with altitude. At the top of the mesosphere, air temperature reaches its coldest value, approaching −90 degrees Celsius (−130 degrees Fahrenheit). The air is extremely thin at this level, with 99.9 percent of the atmosphere’s mass lying below the mesosphere. However, the proportion of nitrogen and oxygen at these levels is about the same as that at sea level. Because of the tenuousness of the atmosphere at this altitude, there is little absorption of solar radiation, which accounts for the low temperature. In the upper parts of the mesosphere, particulates may be present because of the passage of comets or micrometeors. Lidar measurements made by Kent et al. (1971) and Poultney (1972) seem to indicate that particulates in the mesosphere may also be associated with the passage of the earth through the tail of comets. They also show that the particulates at this level are rapidly mixed down to about 40 km. Because of the inaccessibility of the upper layers of the atmosphere for in situ measurements, lidar remote sensing is one of the few effective methods for the examination of processes in these regions.

In the region between 75 and 110 km, there exists a layer containing high concentrations of sodium, potassium, and iron (~3000 atoms/cm³ of Na maximum and ~300 atoms/cm³ of K maximum centered at 90 km and ~11,000 atoms/cm³ of Fe centered about 86 km). The two sources of these alkali atoms
are meteor showers and the vertical transport of salt near the two poles when stratospheric circulation patterns break down (Megie et al., 1978). A large number of lidar studies of these layers have been done with fluorescence lidars (589.9 nm for Na and 769.9 nm for K). A surprising amount of information can be obtained from the observation of the trace amounts of these ions including information on the chemistry of the upper atmosphere (see for example, Plane et al., 1999). Temperature profiles can be obtained by measurement of the Doppler broadening of the returning fluorescence signal (Papen et al., 1995; von Zahn and Hoëfner, 1996; Chen et al., 1996). Profiles of concentrations have been used to study mixing in this region of the atmosphere (Namboothiri et al., 1996; Clemesha et al., 1996; Hecht et al., 1997; Fritts et al., 1997). Illumination of the sodium layer has also been used in adaptive imaging systems to correct for atmospheric distortion (Jeys, 1992; Max et al., 1997).

The mesosphere is bounded above by the mesopause and below by the stratopause. The average height of the mesopause is about 85 km (53 miles). At this altitude, the atmosphere again becomes isothermal. This occurs around the 0.005 mb (0.0005 kPa) pressure level. Below the mesosphere is the stratosphere.

**Stratosphere.** The stratosphere is the layer between the troposphere and the mesosphere, characterized as a stable, stratified layer (hence, stratosphere) with a large temperature inversion throughout its depth. The stratosphere acts as a lid, preventing large storms and other weather from extending above the tropopause. The stratosphere also contains the ozone layer that has been the subject of great discussion in recent years. Ozone is the triatomic form of oxygen that strongly absorbs UV light and prevents it from reaching the earth’s surface at levels dangerous to life. Molecular oxygen dissociates when it absorbs UV light with wavelengths shorter than 250 nm, ultimately forming ozone. The maximum concentration of ozone occurs at about 25 km (15 miles) above the surface, near the middle of the stratosphere. The absorption of UV light in this layer warms the atmosphere. This creates a temperature inversion in the layer so that a temperature maximum occurs at the top of the layer, the stratopause. The stratosphere cools primarily through infrared emission from trace gases. Throughout the bulk of the stratosphere and the mesosphere, elastic lidar returns are almost entirely due to molecular scattering. This enables the use of the lidar returns to determine the temperature profiles at these altitudes (see Section 12.3.1). In the lower parts of the stratosphere, particulates may be present because of aircraft exhaust, rocket launches, or volcanic debris from very large events (such as the Mount St. Helens or Mount Pinatubo events). Particulates from these sources are seldom found at altitudes greater than 17–18 km.

The stratosphere is bounded above by the stratopause, where the atmosphere again becomes isothermal. The average height of the stratopause is about 50 km, or 31 miles. This is about the 1-mb (0.1 kPa) pressure level. The layer below the stratosphere is the troposphere.
Troposphere. The troposphere is the lowest major layer of the atmosphere. This is the layer where nearly all weather takes place. Most thunderstorms do not penetrate the top of the troposphere (about 10 km). In the troposphere, pressure and density rapidly decrease with height, and temperature generally decreases with height at a constant rate. The change of temperature with height is known as the lapse rate. The average lapse rate of the atmosphere is approximately 6.5°C/km. Near the surface, the actual lapse rate may change dramatically from hour to hour on clear days and nights. A distinguishing characteristic of the troposphere is that it is well mixed, thus the name troposphere, derived from the Greek tropein, which means to turn or change. Air molecules can travel to the top of the troposphere (about 10 km up) and back down again in a just a few days. This mixing encourages changing weather. Rain acts to clean the troposphere, removing particulates and many types of chemical compounds. Rainfall is the primary reason for particulate and water-soluble chemical lifetimes on the order of a week to 10 days.

The troposphere is bounded above by the tropopause, a boundary marked as the point at which the temperature stops decreasing with altitude and becomes constant with altitude. The tropopause has an average height of about 10 km (it is higher in equatorial regions and lower in polar regions). This height corresponds to about 7 miles, which is approximately equivalent to the 200-mb (20.0 kPa) pressure level. An important sublayer is the PBL, in which most human activity occurs.

Boundary Layer. This sublayer of the troposphere is the source of nearly all the energy, water vapor, and trace chemical species that are transported higher up into the atmosphere. Human activity directly affects this layer, and much of the atmospheric chemistry also occurs in this layer. It is the most intensely studied part of the atmosphere. The PBL is the lowest 1–2 km of the atmosphere that is directly affected by interactions at the earth’s surface, particularly by the deposition of solar energy. Stull (1992) defines the atmospheric boundary layer as “the part of the troposphere that is directly influenced by the presence of the earth’s surface, and responds to surface forcings with a time scale of about an hour or less.” Because of turbulent motion near the surface and convection, emissions at the surface are mixed throughout the depth of the PBL on timescales of an hour.

Figure 1.2 and the figures to follow are lidar vertical scans that show the lidar backscatter in a vertical slice of the atmosphere. The darkest areas indicate the highest amount of scattering from particulates, and light areas indicate areas with low scattering. Figure 1.2 illustrates a typical daytime evolution of the atmospheric boundary layer in high-pressure conditions over land. Solar heating at the surface causes thermal plumes to rise, transporting moisture, heat, and particulates higher into the boundary layer. The plumes rise and expand adiabatically until a thermodynamic equilibrium is reached at the top of the PBL. The moisture transported by the thermal plumes may form convective clouds at the top of the PBL that will extend higher into the tropos-