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V. E. Zuev I. E. Naats

Inverse Problems of Lidar Sensing of the Atmosphere

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Preface

This monograph undertakes to present systematically the methods for solving inverse problems of lidar sensing of the atmosphere, with emphasis on lidar techniques that are based on the use of light scattering by aerosols. The theory of multi-frequency lidar sensing, as a new method for studying the microphysical and optical characteristics of aerosol formations, is also presented in detail. The possibilities of this theory are illustrated by the experimental results on microstructure analysis of tropospheric and low stratospheric aerosols obtained with ground-based two- and three-frequency lidars. The lidar facilities used in these experimental studies were constructed at the Institute of Atmospheric Optics SB USSR Academy of Sciences. Some aspects of remote control of dispersed air pollution using lidar systems are also considered.

A rigorous theory for inverting the data of polarization lidar measurements is discussed, along with its application to remote measurement of the complex index of refraction of aerosol substances and the microstructure parameters of background aerosols using double-ended lidar schemes. Solutions to such important problems as the separation of contributions due to Rayleigh-molecular and Mie-aerosol light scattering into the total backscatter are obtained by using this theory. Lidar polarization measurements are shown to be useful in this case. The efficiency of the methods suggested here for interpreting the lidar polarization measurements is illustrated by experimental results on the investigation of the microphysical parameters of natural aerosols and artificial smokes using polarization nephelometers.

A brief discussion is also given of the inverse problems related to the remote sensing of profiles of such atmospheric parameters as humidity, temperature, wind velocity, and characteristics of atmospheric turbulence.

We are indebted to our co-workers at the Institute of Atmospheric Optics for the fruitful collaboration that provided the results for this book, and we should like to express our particular appreciation to B.S. Kostin, E.V. Makienko, V.V. Veretennikov, and B.P. Ivanenko, all at the Laboratory of Inverse Problems of Atmospheric Optics. We are also very grateful to T.V. Kuznetsova and N.P. Malincheva for typing the manuscript, and to all those other people who helped us in preparing the graphic material.

Tomsk, March 1982 *V.E. Zuev · I.E. Naats*

Contents

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1. Introduction

The first papers devoted to atmospheric research by means of lasers appeared just after their discovery. Two circumstances were decisive in this situation. First, the development of new facilities for remotely measuring atmospheric parameters was urgently needed. Secondly, lasers were found to be very promising for use in atmospheric research.

As a matter of fact, conventional methods for measuring atmospheric parameters are as yet incapable of obtaining the bulk of specialized information (over space and time) that is required for solving the very important problem of long-range weather forecasting. In addition, the standard method being used in the world-wide meteorological network cannot provide operative information on atmospheric pollution produced by industrial facilities.

The main disadvantages of standard methods are caused by the inherently low spatial and temporal resolutions they can offer, as well as by the limited number of the parameters sounded (e.g., pressure, temperature, humidity, wind). These methods are also characterized by relatively low heights of measurements and by the low accuracy with which the humidity can be determined in the upper troposphere and stratosphere.

The principal way to overcome these difficulties is to develop basically new methods for remotely measuring the atmospheric parameters. Laser methods occupy a special place among those methods and their rapid development began as soon as the first lasers appeared [1.1].

The advantages of the laser methods for sensing the atmospheric parameters, as compared with those of other remote methods (radar, acoustic, spectroscopy of emitted radiation) are a result of the significant number of sufficiently strong interactions accompanying the propagation of light through the atmosphere [1.2]. The following effects should be mentioned among those interactions: Rayleigh scattering by molecules; light scattering by aerosols; spontaneous, stimulated, and resonance Raman effects; absorption of radiation by molecules; Doppler and collisional broadening of molecular absorption lines; Doppler frequency shifts due to scattering on moving inhomogeneities; amplitude and phase fluctuations due to turbulent effects in the atmosphere; as well as a series of nonlinear effects observed at certain powers and pulse durations of the laser radiation. Laser methods provide, in principle, the ability to study atmospheric processes in a real time scale. The information on these processes enters the receiver in a "coded" form at the speed of light. Therefore, if the methods for "decoding" it are known, i.e., one knows the solution of the corresponding inverse problems, final results can be obtained in a time interval determined by the capabilities of the digital data acquisition system used.

In general, the pulse of backscattered radiation from the atmosphere contains information on the profiles of the atmospheric parameters along the sounding paths. The spatial resolution of sounding is determined by the sounding pulse duration. Commonly used lasers have pulse durations of about tens of nanoseconds, which provide a spatial resolution of several meters if, and only if, the digital data acquisition system being used possesses a corresponding time response.

In recent years lasers have become available that deliver 10^3-10^4 pulses per second with a pulse duration of about 10^{-8} s. The use of such lasers in lidar facilities makes it possible, in principle, to obtain up to 10^4 profiles with a spatial resolution of about 1 m within one second.

Lidar methods can be expected to be widely used in the investigation and monitoring of atmospheric aerosol and gaseous pollution from industrial sources [1.2]. There is no doubt about their advantages in comparison with the methods currently in use. They are especially advantageous for investigating the dynamics of air-pollution diffusion.

Light scattering by aerosols is the phenomenon most widely used in lidar studies of the atmosphere. It allows, first of all, the study of atmospheric aerosol distribution. Here not only the distribution of aerosol mass concentration and aerosol stratification are meant, but also the spatial behavior of such microphysical parameters of atmospheric aerosols as size spectra, complex index of refraction, and shape of particles [1.3,4].

Light scattering by aerosols can also be used for sounding atmospheric humidity profiles as well as the profiles of other atmospheric molecular constituents and for measuring wind speed and characteristics of atmospheric turbulence [1.5,6]. In such measurements, aerosols serve as tracers for obtaining information on different atmospheric parameters.

The many promising prospects for using aerosol light scattering for lidar sounding of atmospheric parameters and aerosols as well as the very important role of aerosols in radiation transfer [1.7] and various physico-chemical processes in the atmosphere, including atmospheric pollution, were the main reasons that extensive investigations on the development of various lidar methods have been undertaken in the Institute of Atmospheric Optics SB USSR Academy of Sciences. This monograph summarizes the most important results of the theoretical and experimental studies that have been carried out during the last decade at this Institute under the leadership of the authors.

The book consists of five chapters. The second chapter is devoted to the general theory of optical sounding of polydispersed aerosol systems. An analysis is presented of the basic functional relationships between optical characteristics of dispersed media and their microphysical parameters. The Fredholm integral equation of the first kind is considered as a basic mathematical model. The possibilities of using this equation in problems of lidar sounding of dispersed media are studied, taking into account the morphology of aerosol particles.

The third chapter presents the theory of multifrequency lidar sounding aimed at obtaining information about aerosol microphysical parameters. In parallel with the theory, a justification of the inversion algorithm is given for numerically interpreting the data of optical measurements. Some particular applications of this method for the solution of various practical problems are also included. The capabilities of this method are illustrated with the results of three-frequency lidar sounding of microstructure parameters of tropospheric and stratospheric aerosols.

The material discussed in the third chapter clearly demonstrates the high efficiency of the multifrequency lidar technique suggested for studying aerosol microphysical parameters. There is no doubt that multifrequency lidar is the most advantageous technique for optical sounding of aerosols at the present time.

The fourth chapter presents a discussion of the inverse problem for polydispersed scattering phase matrices. The method for determining simultaneously the refractive index of an aerosol substance and the microstructure parameters of aerosol ensembles is also presented. Its possibilities are illustrated using experimental data. Some methods for solving the inverse problems of bistatic lidar sounding are presented, and the generalized mathematical scheme for inverting the data of sounding obtained with the use of combined mono- and bistatic schemes is discussed. Such a combined sounding scheme allows separating the contributions due to Rayleigh molecular and aerosol Mie scatterings and evaluating the aerosol microphysical parameters. The material presented also demonstrates the promising possibilities of using polarization characteristics of lidar returns for the remote determination of aerosol chemical composition which is of great importance in air pollution control. In addition, the polarization characteristics of lidar returns allow, in principle, the study of the shape and spatial orientation of aerosol particles.

The fifth chapter of the book presents a description of methods and results on sensing different atmospheric parameters using light scattering by aerosols. This chapter also presents the differential absorption lidar technique and its applications to the sounding of the profiles of atmospheric water vapor and ozone. The authors further describe the logarithmic derivative method and discuss its application to the determination of such atmospheric parameters as humidity, temperature, and aerosol characteristics. The questions on lidar sounding of wind speed and parameters of atmospheric turbulence are also briefly discussed.

The concluding remarks contain a summary of the material presented in the monograph and a discussion of possible future developments of the lidar method for sounding the atmospheric parameters based on the use of light scattering by aerosols.

2. Theory of Optical Sensing in Aerosol Polydispersed Systems

Optical methods for investigating aerosol formations in the atmosphere are in fact indirect methods and therefore their use in practice is, as a rule, connected with the solution of systems of functional equations. These are, first of all, the transfer equations for optical signals propagating through the scattering atmosphere, and, secondly, the relationships between optical characteristics and microphysical parameters of the aerosol systems. These relations lead, as a rule, to integral equations of the first kind in studies of microstructures of atmospheric aerosols by the methods of optical sounding. The equations are one-dimensional if sphericity of the particles is assumed.

In the general case of an arbitrary particle shape, the determination of the microstructures of such polydispersed systems requires the solution of multi-dimensional equations as well as the performance of very complicated optical experiments. It is obvious that the solution of the inverse problems of light scattering in the form of one-dimensional integration equations is the simplest approximate method for determining the microstructures of real dispersed media. This is why the first problem of optical sounding theory is to assess the possibility of investigating the microstructures of atmospheric aerosols using optical methods based on the solution of one-dimensional inverse problems of light scattering. A detailed analysis of this problem is given in this chapter by an example of the determination of the microstructure of a polydispersed system of convex particles randomly oriented in an illuminated volume.

The efficiency of the optical data inversion and, as a consequence, of the optical methods depends also on the choice of a kernel in a corresponding integral equation [2.1]. Only in the case of spherical particles can such a choice easily be made, since in this case the working apparatus for the solution of inverse problems is the Mie theory [2.2]. A detailed description of the theory and methods for determining the scattering efficiency

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