Journal of Quantitative Spectroscopy & Radiative Transfer 149 (2014) 16–32

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

# Detection of preferential particle orientation in the atmosphere: Development of an alternative polarization lidar system

Manfred Geier *, Marco Arienti

*Sandia National Laboratories, Livermore, CA 94551, United States*

ARTICLE INFO

*Article history:*
Received 13 February 2014
Received in revised form
11 July 2014
Accepted 12 July 2014
Available online 19 July 2014

*Keywords:*
Light scattering
Remote sensing
Lidar
Polarization
Aerosol

ABSTRACT

Increasing interest in polarimetric characterization of atmospheric aerosols has led to the development of complete sample-measuring (Mueller) polarimeters that are capable of measuring the entire backscattering phase matrix of a probed volume. These Mueller polarimeters consist of several moving parts, which limit measurement rates and complicate data analysis. In this paper, we present the concept of a less complex polarization lidar setup for detection of preferential orientation of atmospheric particulates. On the basis of theoretical considerations of data inversion stability and propagation of measurement uncertainties, an optimum optical configuration is established for two modes of operation (with either a linear or a circular polarized incident laser beam). The conceptualized setup falls in the category of incomplete sample-measuring polarimeters and uses four detection channels for simultaneous measurement of the backscattered light. The expected performance characteristics are discussed through an example of a typical aerosol with a small fraction of particles oriented in a preferred direction. The theoretical analysis suggests that achievable accuracies in backscatter cross-sections and depolarization ratios are similar to those with conventional two-channel configurations, while in addition preferential orientation can be detected with the proposed four-channel system for a wide range of conditions.



## 1. Introduction

Lidar techniques have been applied since the late 1960s and have become indispensable tools for characterization of the atmosphere [1]. The laser light used to interrogate the atmosphere leaves the dynamics of the probed fluid unperturbed and therefore enables characterization of conditions in the atmosphere with high temporal and spatial resolution. Polarization lidar systems provide information on changes in the polarization state induced by the scatterers in the probed volume element, which are commonly quantified in terms of changes in the overall backscatter coefficient and in the linear (or circular) depolarization ratio [2]. The backscatter coefficient quantifies the amount of light scattered into the backward direction and thus characterizes the optical properties of a probed region in the atmosphere [1]. Depolarization ratios have been used extensively to discriminate between ice and water phases in clouds [2–8], and serve as indicators for multiple scattering and for the presence and discrimination of nonspherical scatterers [9,10]. Preferential orientation of nonspherical particles may result in significantly higher (or lower) effective cross-sections for extinction of incident radiation than expected from orientation-averaged cross-sections, and

* Corresponding author.
*E-mail addresses:* manfred.geier@gmx.net (M. Geier), marient@sandia.gov (M. Arienti).

http://dx.doi.org/10.1016/j.jqsrt.2014.07.011
0022-4073/

may thus cause significantly more (or less) participation in radiative energy exchange. An example reported in this paper shows that the scattering cross-sections for the studied particles vary over more two orders of magnitude depending on the particle orientation relative to the propagation direction of the incident light.

Kaul et al. [11] showed with their measurements of the backscatter phase matrix that large hexagonal faces of ice crystals in cirrus clouds tend to align with a horizontal plane, and produce visually observable sundogs and light pillars. Airborne particulates, mostly inorganic dust particles, biogenic particles, and soot aggregates [12], are considerably smaller than ice crystals (a few nanometers to several micrometers *versus* tens of micrometers to several millimeters) [13], and typically have nonspherical shapes. For these particulates, gravitational, fluid dynamic, electric and magnetic forces have conveniently been assumed to be ineffective in producing appreciable particle orientation, but the validity of that assumption has been questioned in recent years based on theoretical considerations and experimental evidence [14,15]. Whether caused by preferential orientation or by insufficient population size (when the number of particles of a kind is too small for each sampled particle to have a particle in reciprocal orientation present), an imbalance in the particulate orientation may lead to erroneous interpretation of depolarization ratios. Measurements sensitive to detecting particle ordering therefore complement traditional depolarization measurements and could provide valuable insight into atmospheric aerosol dynamics, enabling better, unbiased interpretation of lidar returns.

Over the past 40 years, the merits of measured depolarization ratios in the characterization of atmospheric aerosols have led to wide-spread application of polarization lidar systems in various configurations. Early systems fall into the category of the Stokes polarimeters (or light-measuring polarimeters [16]), which measure the polarization states of the returning light. For instance, Pal and Carswell used a three-channel system to determine the first three Stokes parameters $I, Q$, and $U$ [17]. A four-channel Stokes polarimeter has been investigated by Houston and Carswell [18], who, based on their findings, concluded that the increased complexity outweighs the benefits of four-component measurements and recommended two-channel measurements as the most efficient lidar approach [18]. The system described in [3] uses two channels for detection, but it is capable of measuring the full Stokes vector of the backscattered light by utilizing three switchable ferroelectric cells together with a quarter-wave plate to vary the polarization states for signal generation and analysis. The instrument allows for quasi-simultaneous measurement of both linear and circular depolarization ratio, and was proposed mainly for detection of oriented ice platelets in clouds. A single-detector system with similarly switched polarization states of the incident beam is described in [19].

Mueller-matrix polarimetric lidar systems for measurement of the entire backscatter matrix have been described by Kaul et al. [11], and more recently by Hayman et al. [20] (these systems are considered complete sample-measuring polarimeters [16] for their ability to fully determine the backscatter matrix). Since preferential orientation can be detected through evaluation of the magnitudes of off-diagonal elements of the backscatter phase matrix, these systems can provide information regarding the presence of oriented particles. However, for the measurement of a scattering matrix it is necessary to vary polarization states of both sounding beam and analyzers, which is commonly achieved by means of rotating retarders [21]. The scattering matrix from these measurements is thus determined by combining signals acquired at different sampling times. The results are consequently only reliable if the probed sample is temporally sufficiently stable. Validity of this assumption is clearly questionable in the light of inherent temporal and spatial variability of composition and characteristics of atmospheric aerosols. Variation of the retardances with rotation angle may produce additional systematic error, and spatial and temporal resolutions are limited by the maximum rotation speeds to maintain well-controlled alignment of retarders.

As an alternative to these Mueller polarimeters, we investigate a polarization lidar setup with stationary, standard optical components in this study. The conceptualized system is free of moving parts and therefore more robust, and permits faster sampling rates than conventional Mueller polarimeters. It is, however, an incomplete sample-measuring polarimeter that provides information only for a subset of backscatter matrix elements. This solution is still adequate for approximate characterization of the probed volume, and in addition has the potential of providing data with increased spatial and temporal resolution. This new concept can thus be placed between the afore-mentioned complete Mueller polarimeters and Stokes polarimeters. Accepting partial information on the backscatter phase matrix enables reduction of the instrument complexity that translates to increased reliability, which is particularly important for applications in extreme environments such as the Arctic region. Application of high-quality lasers, detectors and data acquisition equipment with the outlined system enables measurements with higher spatial and temporal resolution than polarimeters with rotating optical components. The absence of moving parts facilitates processing of detected signals because of the less-demanding need for component modeling to properly account for imperfections and angular alignment uncertainties. The design concept of the instrument features simultaneous measurement of all pieces of information that are used in the data inversion. This eliminates uncertainties associated with temporal variabilities in the probed aerosol, and facilitates application of advanced denoising approaches to the recorded data stream.

In this theoretical study, we explore the feasibility of such a polarization lidar system for the measurement of the degree of preferential orientation, depolarization ratio, and backscatter coefficient. Specifically, our focus lies on theoretical development of configurations that exhibit optimal measurement stability when the polarization state of the incident probe beam is held fixed. For the development, we first discuss the general structure of the backscatter phase matrix and establish combinations of matrix elements suitable for indication of preferential orientation. We then determine the configuration of a four-channel