Journal of Quantitative Spectroscopy & Radiative Transfer 210 (2018) 180–188

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

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

Extinction effects of atmospheric compositions on return signals of space-based lidar from numerical simulation

Lilin Yao [a,b], Fu Wang [b], Min Min [b,*], Ying Zhang [a,*], Jianping Guo [c], Xiao Yu [b,d], Binglong Chen [b], Yiming Zhao [e], Lidong Wang [e]

[a] School of Resources and Environment, University of Electronic Science and Technology of China, Chengdu, Sichuan 610054, China
[b] Key Laboratory of Radiometric Calibration and Validation for Environmental Satellites (LRCVES/CMA), National Satellite Meteorological Center, China Meteorological Administration (NSMC/CMA), Beijing 100081, China
[c] State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100081, China
[d] College of Electronic Engineering, Chengdu University of Information Technology, Chengdu, Sichuan 610103, China
[e] Beijing Research Institute of Telemetry, Beijing 100094, China

ARTICLE INFO

Article history:
Received 8 November 2017
Revised 19 December 2017
Accepted 29 January 2018
Available online 3 February 2018

Keyword:
Space-based lidar
Simulation
Aerosol
Spectral transmittance
SNR

ABSTRACT

The atmospheric composition induced extinction effect on return signals of space-based lidar remains incomprehensively understood, especially around 355 nm and 2051 nm channels. Here we simulated the extinction effects of atmospheric gases (e.g., H_2O, CO_2, and O_3) and six types of aerosols (clean continental, clean marine, dust, polluted continental, polluted dust, and smoke) on return signals of space-based lidar system at 355 nm, 532 nm, 1064 nm, and 2051 nm channels, based on a robust lidar return signal simulator in combination with radiative transfer model (LBLRTM). Results show significant Rayleigh (molecular) scattering effects in the return signals at 355 nm and 532 nm channels, which markedly decays with increases in wavelength. The spectral transmittance of CO_2 is nearly 0, yet the transmittance of H_2O is approximately 100% at 2051 nm, which verifies this 2051 nm channel is suitable for CO_2 retrieval. The spectral transmittance also reveals another possible window for CO_2 and H_2O detection at 2051.6 nm, since their transmittance both near 0.5. Moreover the corresponding Doppler return signals at 2051.6 nm channel can be used to retrieve wind field. Thus we suggest 2051 nm channel may better be centered at 2051.6 nm. Using the threshold for the signal-to-noise ratio (SNR) of return signals, the detection ranges for three representative distribution scenarios for the six types of aerosols at four typical lidar channels are determined. The results clearly show that high SNR values can be seen ubiquitously in the atmosphere ranging from the height of aerosol layer top to 25 km at 355 nm, and can been found at 2051.6 nm in the lower troposphere that highly depends on aerosol distribution scenario in the vertical. This indicates that the Doppler space-based lidar system with a double-channel joint detection mode is able to retrieve atmospheric wind field or profile from 0 to 25 km.

1. Introduction

Lidar emits laser pulses to target, and then determines the target distance, azimuth, elevation, state of motion, and other physical properties by measuring the arrival time, intensity, frequency changes, and other parameters of backscattering return signals received by telescope [1]. In the atmospheric science field, lidar is often used to detect or measure a variety of atmospheric parameters, such as physical and optical properties of cloud and aerosol, atmospheric temperature and humidity, atmospheric gases, wind field or profile, etc. [2]. Compared with traditional ground-based lidar system [3,4], space-based lidar system [5,6] can better detect or profile global atmospheric parameters (i.e. cloud and aerosol), and help us improve our understanding of their corresponding climatology and variation trends [7,8]. However, currently only several Mie scattering lidars have been successfully launched into space for detecting cloud, aerosol, and surface elevation [5,6,9-11]. In 2006, the Cloud-Aerosol and Infrared Pathfinder Satellite Observations (CALIPSO) satellite program was successfully launched as a component of the U.S. National Aeronautics and Space Administration (NASA) Afternoon Constellation (“A-Train”) [9,12], which has been operationally running for more than 11 years so far. The pri-

---

[*] Corresponding authors.

E-mail addresses: minmin@cma.gov.cn (M. Min), zhangyingxf@uestc.edu.cn (Y. Zhang).

https://doi.org/10.1016/j.jqsrt.2018.01.034

mary payloads installed on CALIPSO are a dual-wavelength and polarization backscatter lidar (i.e. two orthogonally polarized 532 nm channel and a 1064 nm channel), an imaging infrared radiometer, and a wide field camera [13]. Recently, the Cloud-Aerosol Transport System (CATS) as a successor of CALISPO for the global atmospheric measurements has been installed on the International Space Station (ISS) by NASA in 2015 [14,15]. The Active Sensing of CO_2 Emissions over Nights Days and Seasons (ASCENDS) mission, NASA wants to use active sensing (lidar) to measure the amount of CO_2 in the air so that it can't only work under daylight conditions but also at night time [16]. It is worth noting that a Terrestrial Ecosystem Observation Satellite Program (TEOSP) and an Atmospheric Environmental Monitoring Satellite Program (AEMSP) have been scheduled to be simultaneously launched during 2019-2020 in China. TEOSP will install a lidar with the similar specifications of CALIPSO [17], including 532 nm (polarization) and 1064 nm channels. AEMSP will use the dual-wavelength (532 nm and 1064 nm), polarization detection and high spectral resolution (at 532 nm) lidar technology to realize the cloud and aerosol detection, and use the 1572 nm wavelength differential absorption lidar technology to detect CO_2. The acquisition and assimilation of the reliable global 3D atmospheric wind field data could significantly improve the accuracy of numerical weather prediction (NWP) and better serve the climate research community [17]. The accurate measurement of 3D wind field is very difficult to be measured or detected by current space-based sensors, particularly the three-dimension (3-D) wind field data [18]. Therefore, the World Meteorological Organization (WMO) has placed the global wind profile detection as the first priority of numerical weather forecasts [16]. The space-based Doppler wind lidar can directly collect a sequence of Doppler frequency shift along laser light beam. The magnitude of Doppler frequency shift depends on the velocity of the scattering particles that moves with the airflow [18]. Thus, it will become a useful tool for retrieving the 3D structure of the global atmospheric wind field in future [19]. However, the European Space Agency (ESA) has decided to delay the launch of the Atmospheric Dynamic Mission (ADM-Aeolus) due to the laser technology problem, which is rescheduled to launch into the 408 km height of the sun synchronous orbit equipped with an Atmosphere Laser Doppler Instrument (Aladin) at 355 nm wavelength in 2018 [20]. Besides, another important space-based Doppler wind lidar mission is the Global Wind Observing System (GWOS) programmed by NASA, which uses the pulsed hybrid Doppler wind lidar system with a combination of a coherent detection system at 355 nm and a detection system at 2.0 µm for detecting molecular and aerosol scattering return signals, respectively [17,21].

Theoretically, no matter what kind of space-based lidar detection systems, the emitted and received laser beam between space-based lidar and the Earth's surface inevitably interact with various atmospheric compositions in the atmosphere, such as atmospheric molecules, gases, and aerosol particulates. Absorption and scattering effects of atmospheric compositions along laser beam transmission path are able to significantly change the energy or property of laser beam. Specifically, the absorption effects of atmospheric gases mainly depend on their absorption intensity at a given wavelength and total amount in the atmosphere [22]. Based on the wavelength-dependent absorption effect of gas molecules, the laser beam is not only remarkably attenuated, but also can be used to quantitatively retrieve the concentration or total content of the corresponding absorbing gas. For instance, the lidar channel at 2.0 µm wavelength is suitable for retrieving CO_2 amount [23]. Similar to gas molecules, aerosol also plays an important role in the laser beam transmission process due to its absorption and scattering effects [24]. Actually, this optical extinction (absorption and scattering) effect due to aerosol particles has been successfully used to discriminate aerosol type and retrieve aerosol optical coefficients in the current space-based lidar operational algorithms [25,26]. Even though the space-based lidar for detecting global atmospheric wind field or profile is based on Doppler frequency shift effect [27], the emitted and received laser beams will also be significantly scattered and absorbed by atmospheric components along laser beam transmission path. The changes in return signals of space-based lidar induced by this effect are more likely to exert great influences on the final retrieval quality of wind field or profile data.

However, the related studies on the extinction effects of gases and aerosol particulates on detecting capabilities of return signals for various space-based lidars are seldom well documented. Therefore, the primary objective of this study is to explore the potential impacts of atmospheric components on space-based lidar return signals, and to help us further design and develop the new-generation space-based lidar systems of TEOSP and AEMSP in China. An advanced and robust space-based lidar return signal simulator for atmospheric measurement is designed in this study. Based on the simulator along with the radiative transfer model, the extinction effects of gases and aerosol particulates have been investigated on return signals or detection ranges of space-based lidars for four typical lidar channels at 355 nm, 532 nm, 1064 nm, and 2051 nm (personal communication). Section 2 illustrates the detailed method how we make the simulator at four typical lidar channels. In Section 3, several numerical experiments reveal the absorption effect of primary gases on laser beam. The extinction effects of six different types of aerosols on space-based lidar detection ranges are also simulated and demonstrated. The primary conclusions are summarized in Section 4.

2. Space-based lidar simulator

2.1. Lidar transmission equation

To better investigate the extinction effects of atmospheric compositions on space-based lidar return signals, a numerical simulator for modeling space-based lidar return signal is made under the classical lidar transmission equation [28], in which the return signal, P, can be written as:

$$P(z,\lambda) = C\left(\frac{\cos(\theta)}{z - z_s}\right)^2 [\beta_m(z,\lambda) + \beta_a(z,\lambda)]T^2(z - z_s), \tag{1}$$

where z_s is the altitude of space-based platform, z is the target altitude above the sea surface level, and $(z_s - z)$ is the distance from target to space-based lidar telescope. λ is the wavelength. C is the lidar system constant, which is measured before launch. θ is the off-nadir zenith angle of received telescope. $\beta_m(z,\lambda)$ and $\beta_a(z,\lambda)$ represent the backscattering coefficient of molecules and aerosols, respectively. Double-path transmittance of $T^2(z)$ can be defined as the integral expression of extinction coefficient $\int_{z_s}^{z}\alpha(z')dz'$, the integration with respect to the range z' can be written as:

$$T^2(z - z_s) = \exp\left[-2\int_{z_s}^{z}\alpha\left(z'\right)dz'\right], \tag{2}$$

where $\alpha(z)$ is the extinction coefficient. Both molecular and aerosol components contribute to the extinction coefficient $\alpha(z) = \alpha_m(z) + \alpha_a(z)$. Its relationship with backscattering coefficient, β, can be expressed as:

$$\alpha(z) = S\beta(z) = S_m\beta_m(z) + S_a\beta_a(z), \tag{3}$$

where S is the lidar ratio (LR) or extinction-to-backscattering ratio. The subscripts m and a respectively represent atmospheric molecular and aerosol. In appropriate standard atmosphere model, for the molecular scattering, S_m is the constant $8\pi/3$ [29].