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Retrievals of aerosol microphysics from simulations of spaceborne multiwavelength lidar measurements

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ABSTRACT

In support of the Aerosol, Clouds, Ecosystems mission, simulations of a spaceborne multiwavelength lidar are performed based on global model simulations of the atmosphere along a satellite orbit track. The yield for aerosol microphysical inversions is quantified and comparisons are made between the aerosol microphysics inherent in the global model and those inverted from both the model's optical data and the simulated three backscatter and two extinction lidar measurements, which are based on the model's optical data. We find that yield can be significantly increased if inversions based on a reduced optical dataset of three backscatter and one extinction are acceptable. In general, retrieval performance is better for cases where the aerosol fine mode dominates although a lack of sensitivity to particles with sizes less than 0.1 µm is found. Lack of sensitivity to coarse mode cases is also found, in agreement with earlier studies. Surface area is generally the most robustly retrieved quantity. The work here points toward the need for ancillary data to aid in the constraints of the lidar inversions and also for joint inversions involving lidar and polarimeter measurements.

1. Introduction

NASA's involvement in space lidar systems dates from the Apollo era when a laser altimeter was flown on Apollo 15, 16 and 17 in 1971–72 (http://www.lpi.usra.edu/lunar/missions/apollo/apollo_17/experiments/la/). Since that time, several NASA missions have used laser altimeters for topographic measurements of both the Earth [1] and other planets [2]. The first NASA lidar mission that measured the Earth's atmospheric profiles was the Lidar In space Technology Experiment (LITE) that flew on the space shuttle Discovery in 1994 for a 10-day technology demonstration mission [3]. In 2006, the CALIOP lidar was launched as part of the CALIPSO mission and continues to make profile measurements of aerosols and clouds into 2017. ESA and JAXA are also making important contributions to space-lidar with the upcoming launch of EarthCARE in 2018 which will offer a High Spectral Resolution Lidar operating at 355 nm that will focus on characterization of cloud fields from space [4,5] and significantly improve characterization of cloud radiative effects in global models.

A future NASA atmospheric profiling mission, the Aerosol, Cloud, Ecosystems (ACE) Mission, was identified as a priority in the 2007 National Research Council Decadal Survey and is anticipated to include NASA's most advanced spaceborne lidar system. The goals of the ACE mission include decreasing the uncertainties associated with the roles of aerosols, clouds and precipitation in the hydrological cycle and climate change. The candidate suite of instruments proposed for the mission includes polarimeter, radar, multiwavelength (MW) High Spectral Resolution Lidar (HSRL) and ocean color spectrometer. NASA is conducting a pre-formulation study to consider science measurement requirements and measurement capabilities of the candidate instrumentation. As a part of that pre-formulation study, we consider here the measurement capability of, and aerosol micro-physical retrievals from, a spaceborne, multiwavelength lidar within the context of the ACE mission. More information on the ACE mission along with the results of community workshops led by the ACE Science Working group can be found at http://dsm.gsfc.nasa.gov/ace/.

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Table 1
Specifications of the spaceborne lidar system used in the simulation study.

Simulated lidar system specifications	
Component/Parameter	Specification
Laser power (1064, 532, 355 nm)	10 W, 10 W, 5W
Laser repetition rate	100 Hz
Telescope diameter	1.5 m
Telescope field of view	130 μ radian
Channel bandwidths (1064, 532, 355 nm)	30 pm, 30 pm, 20 pm
Total optical efficiencies (molecular, particle)	9.6%, 2.4%
Data acquisition technique	Analog
Orbital altitudes studied	450 km, 820 km

2. Aerosol microphysical retrievals using the multiwavelength lidar

The multiwavelength lidar technique has proven useful for estimating the vertical profile of aerosol microphysical parameters such as effective radius, volume and refractive index under widely varying conditions [6–9]. The most common configuration of multiwavelength lidar for such studies is one based on a tripled Nd: YAG laser providing three backscattering and two extinction coefficients (the so called 3ß$+$r$+2\alpha$ dataset). From these data aerosol microphysics can be inverted [10–13], using different inversion approaches [14,15]. It is most common for ground-based systems that Raman scattering is used for the measurements from which aerosol extinction is calculated. However, for spaceborne configurations the HSRL technique [16–18], will be considered in the simulations done here due to its much higher signal-to-noise ratio for the pure molecular measurements. An important consideration in these lidar inversions is that there are only 5 input optical data and, thus, the inverse problem is under-determined [19]. The inverse equations are multi-valued implying that other information is needed to constrain the region over which a solution is sought. Such constraints increase the stability and accuracy of the inversion although the assumptions inherent in the constraints need to be considered an important part of the solution technique. In the context of the ACE mission, additional information from a polarimeter or from lidar depolarization measurements [20], can also aid the lidar inversion by helping to constrain the search space for a solution although those details were not considered here. Additional assumptions about size- and spectrally-independent refractive index are also made in these retrievals [10–12].

3. Hardware configuration

The main purpose of this effort was to perform a relatively simple study to assess the measurements and aerosol microphysical inversions from a spaceborne multiwavelength HSRL lidar. As such, we did not wish to consider the specific detailed optical design of any particular system that might be under development to meet the needs of the ACE mission. We also did not consider clouds. We focused only on the lidar system parameters that determine optical throughput and used them to simulate performance of a spaceborne lidar in a cloud-free atmosphere. To determine the system parameters, we consulted with various manufacturers and lidar specialists to generate the set of parameters shown in Table 1. These parameters are considered to be technically feasible and a reasonable representation of a currently feasible spaceborne HSRL lidar.

4. Simulation approach

The model used in this simulation study is one that was first developed in 1999 [22], in support of the Raman Airborne Spectroscopic Lidar [23], development effort that was funded under NASA's Instrument Incubator Program. That model has been used to simulate both airborne and ground-based lidar systems under a wide range of conditions [24], and is an implementation of the lidar equation [25], that carries physical units through the entire simulation chain including for background skylight. Modifications were made to the molecular cross sections used in the model to permit the simulation of the molecular channels of an HSRL instrument. For all simulated lidar signals, the model generates a profile of photon count rate based on the lidar instrument parameters and the atmospheric profile of aerosol and molecular density provided to the model. For validation of the model, consideration was given to using data from the CALIOP [26], instrument. The CALIOP lidar uses a 22-bit analog data acquisition system with gain switching capability so that the raw output is in digital count values that correlate to a voltage scale. To avoid the complications of converting this voltage value to photon count rate, we chose instead to use Geosciences Laser Altimetry System (GLAS) [27], data from October 9, 2003 since the GLAS system used photon counting electronics. The measured photon count rate from GLAS could, therefore, be directly compared with the lidar simulator's output of photon count rate. Using GLAS instrument parameters, the comparisons of GLAS data with the model output were in excellent agreement including during the passage of the instrument into and out of the terminator region where skylight background is considerable. Beyond a photon count rate of 10–20 Mhz, however, the comparisons degraded due to the non-linear nature of the photon counting process of the GLAS electronics. This limitation did not influence the comparisons done here since the candidate ACE lidar is considered to use an analog detection system which does not possess the non-linear behavior shown in the GLAS photon counting data.

As the basis for the simulations, the GEOS-5 Model [28], was used to simulate the atmospheric conditions along a 24 h track of the CALIOP lidar instrument valid for July 24, 2009. GEOS-5 is an Earth system model, here incorporating an atmospheric general circulation model, representations of atmospheric physics including moist processes, chemistry, and aerosols, and a data assimilation module. The GEOS-5 simulation was run using assimilated meteorology from its own Modern-Era Retrospective Analysis for Research and Applications (MERRA) [29]. Aerosols were run inline and radiatively coupled in GEOS-5 using a version of the Goddard Chemistry, Aerosol, Radiation, and Transport (GOCART) module (based on [30]). The GOCART module includes representations of dust, sea salt, black and organic carbon, and sulfate aerosols. Sulfate and carbonaceous species are carried as bulk mass tracers with additional partitioning between hydrophobic and hydrophilic modes for the carbonaceous aerosols. Sulfate and carbonaceous aerosols are all assumed to be in the fine mode. Sea salt and dust are both represented by a series of five size bins spanning 0.1 – 10 μm radius for dust and 0.03 – 10 μm dry radius for sea salt, allowing for simulation of both the fine and coarse fractions of each. The refractive index of the total aerosol is a volume-weighted average of the individual components, including any aerosol borne water. A more complete description of how GOCART is implemented in the GEOS models is provided in [31], which also includes a detailed evaluation of the module with respect to the aerosol optical depth measurements provided by MODIS, MISR and AERONET. Additionally, Colarco et al. [31] evaluated the Angstrom parameter (i.e., spectral dependence of AOD, which is related to particle size) with respect to AERONET observations, finding a high degree of correlation with the observations but a low bias in the model (i.e., the model tended toward a small overestimate of the coarse mode contribution to the AOD). Optical properties of the aerosols are primarily based on Mie calculations using the particle properties as in Colarco et al. [31] and Chin et al. [30] with spectral refractive indices primarily from the Optical Properties of Aerosols and Clouds [32] database. The exception to this is for dust, updated