A Compact Airborne High Spectral Resolution Lidar for Observations of Aerosol and Cloud Optical Properties

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ABSTRACT

We are in the process of developing a nadir-viewing, aircraft-based high spectral resolution lidar (HSRL) at NASA Langley Research Center. The system is designed to measure backscatter and extinction of aerosols and tenuous clouds. The primary uses of the instrument will be to validate spaceborne aerosol and cloud observations, carry out regional process studies, and assess the predictions of chemical transport models. In this paper, we provide an overview of the instrument design and present the results of simulations showing the instrument's capability to accurately measure extinction and extinction-to-backscatter ratio.

1. INTRODUCTION

Better quantification of extinction due to aerosols and clouds is required to improve the predictive capabilities of climate models. Especially crucial is the vertical profile of extinction, which is extremely difficult to measure accurately. Various passive instruments are used to measure optical depth and many are flying or will be flying on satellites in the next several years (MODIS, MISR, PARASOL, etc.). However, passive instruments suffer from lack of vertical resolution and reduced accuracy over land where aerosol loading, and hence climate forcing, is most significant. Spaceborne backscatter lidars, like CALIPSO and GLAS, and their ground- and aircraft-based relatives, are used to infer extinction profiles; however, the retrieval relies on an assumed extinction-to-backscatter ratio (S), which is highly uncertain.

High spectral resolution lidar (HSRL) overcomes many of the limitations of other remote sensing techniques[1]. HSRL can accurately measure profiles of extinction during night or day, over ocean or land, with high vertical resolution, and with minimal assumptions. HSRL can also be used to measure profiles of S, which can be used along with other data to constrain inferences of particle type or cirrus particle habit. However, only a few groups have demonstrated significant success with the HSRL technique[2,3,4,5], and the systems they have developed have been large, complex laboratory instruments which have been difficult to operate. Fortunately, advances in laser technology have made it possible to consider more compact, robust systems[6]. However, an HSRL system suitable for routine operation on an aircraft has never been developed.

The goal of our effort is to develop a compact, robust, aircraft-based HSRL system suitable for deployment on a small Lear Jet and eventually the NASA WB57. The system will be used to validate the measurements made by the CALIPSO spaceborne lidar as well as aerosol retrievals from satellite-based passive sensors. In addition to validating measurements of extinction and optical depth, the observed profiles of S will be used to improve the algorithms for estimating the value of S used in CALIPSO retrievals of extinction and backscatter. We also intend to fly the system on deployments focused on regional process studies and the validation of chemical transport models.

2. ADVANTAGES OF AIRBORNE HSRL

The HSRL technique takes advantage of the spectral distribution of the backscattered light to discriminate between aerosol/cloud returns and molecular returns. Lidar backscatter from air molecules is Doppler broadened by a few GHz due to the high-velocity random thermal motion of the molecules. Because the aerosol/cloud particles are much heavier than gas molecules, their velocities are much lower, and the resulting Doppler broadening of the aerosol/cloud return is much smaller (tens of MHz). Discrimination between aerosol and molecular returns in the receiver is accomplished by splitting the returned signal into two optical channels, one with an extremely narrow-band absorption filter to eliminate the aerosol returns, and another that passes all frequencies of the returned signal. With appropriate internal calibration, the signals from the two channels can be used to retrieve profiles of extinction, backscatter, and *S* (extinction-to-backscatter ratio). Extinction is computed from the molecular signal channel by comparing the measured molecular-scattered profile, which is attenuated by extinction along the transmit-receive path, to a reference molecular profile (e.g., from rawinsondes or an assimilation model). The aerosol scattering ratio and aerosol backscatter coefficient are computed by appropriate ratioing/differencing of the molecular and total scatter signals. While standard backscatter lidar retrievals rely on an assumed and often highly uncertain value of *S*, the ratio of the HSRL-derived aerosol/cloud extinction and backscatter profiles yield a measurement of *S* itself.

In addition to a more accurate retrieval of extinction and the ability to infer the profile of *S*, another advantage that the HSRL technique has over nadir-viewing aircraft-based backscatter lidars concerns calibration of the backscatter measurement. Backscatter lidars are typically calibrated by comparing the signal from a volume of air assumed to be free of aerosols and clouds to the backscatter coefficient for that volume estimated from a model atmosphere or rawinsonde data. In the case of nadir-viewing airborne backscatter lidars, it can be difficult to find regions in the observed profiles where aerosol loading is negligible and/or recognize such regions when they are encountered. On the other hand, a properly designed HSRL system is calibrated through a combination of laboratory and internal instrument operations. The shape, but not absolute transmission, of the iodine absorption feature is measured in the laboratory. Calibration of the relative optical transmission and detection system gain of the molecular and total backscatter channels is carried out periodically through the course of a flight as described below. These measurements calibrate the HSRL with high precision and accuracy and without reliance on external assumptions.

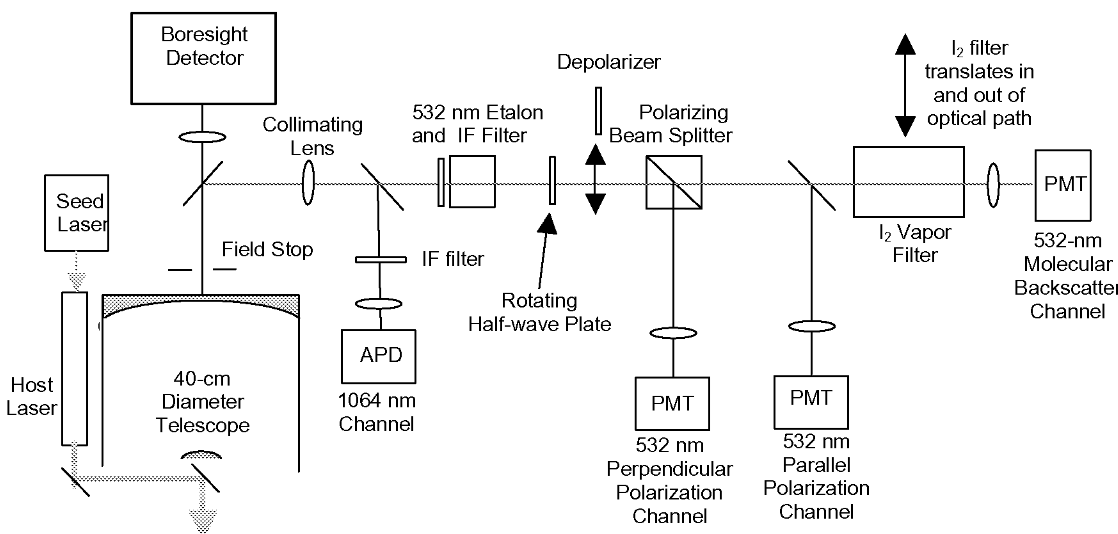

Figure 1. Simplified block diagram of the airborne HSRL optical systems.

3. INSTRUMENT DESCRIPTION

A simplified block diagram of our system is shown in Figure 1. We have added polarization sensitivity to the basic HSRL concept by splitting the total (aerosol plus molecular) backscatter channel into two component channels that measure the backscatter polarized parallel and perpendicular to the polarization plane of the transmitter. In addition, we have added a 1064 nm channel to enable comparisons of the backscatter strength at the two wavelengths. The system therefore provides measurements of three *intensive* optical parameters: *S* at 532 nm, polarization ratio at 532 nm, and the ratio between the 532 and 1064 nm backscatter. These data products depend only on the composition, shape, and size distribution of the scatterers, not their concentration, and will be useful to constrain inferences of aerosol type or cirrus particle habit.

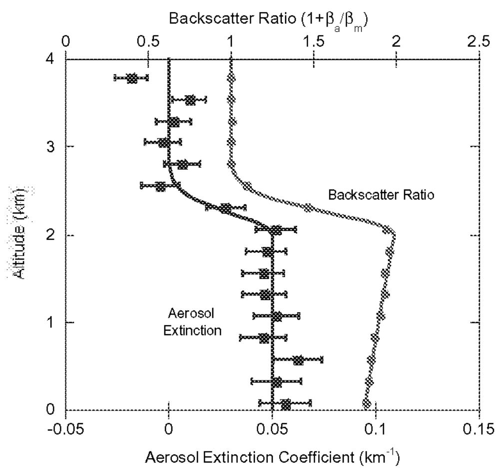

Figure 2. Simulated retrieval of extinction. Aircraft altitude was set at 10 km, and the vertical and horizontal averaging were set to 250 m and 10 km, respectively.

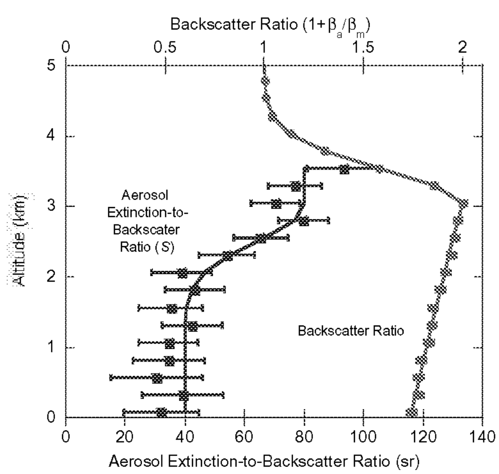

Figure 3. Simulated retrieval of extinction-to-backscatter ration, *S*, for a two-layer system: aerosol with a large black carbon content lofted above continental aerosol with low black carbon content. Aircraft altitude and spatial averaging are as in Fig. 2.

The output energy of the laser is 5 mJ for both wavelengths, and the repetition rate is 200 Hz. To provide adequate SNR for daytime measurements, the receiver FOV will be selectable between 0.5 and 1.0 mrad, and the transmitter divergence will be limited to approximately 100 µrad. Additionally, solar background light is reduced in the 532 nm returns by an interference filter and an etalon. The bandwidth of the etalon is 40 pm. The 1064 channel employs an interference filter only. A boresight detector is included in the design to measure and correct transmitter-receiver misalignment.

Calibration is crucial to obtaining accurate estimates of extinction and intensive optical properties. The polarization reference plane of the receiver is aligned with that of the transmitter via a calibration operation involving a rotating half-wave plate upstream of the polarizing beam splitter. The gains of the detectors in the two polarization channels are calibrated by inserting a pseudo-depolarizer between the half-wave plate and the polarization beam splitter. The gain of the molecular channel is calibrated to the polarization channels by removing the iodine filter from the optical path.

The most technically challenging aspect of the system is the transmitter. The transmitter must have very high spectral purity and must be frequency agile over a small wavelength range to enable tuning to an appropriate iodine absorption line. This is accomplished using a single mode CW seed laser and a high energy pulsed host laser. The seed laser is locked to the center of the iodine line by taking advantage of the Doppler-free absorption spectrum of iodine measured with a separate iodine cell in the laser feedback subsystem. The seed laser for our system was developed by Innolight GmbH and is tunable over a 90 pm wavelength range. Fibertek, Inc, is developing the injection-seeded Nd:YAG host laser. The most difficult aspect of the host laser design is insuring that the laser seeds reliably on a vibrating aircraft platform. We expect to take delivery of the laser in fall of 2002, after which it will undergo rigorous testing. We plan to integrate the transmitter and receiver components during the summer 2003 and test the system on a Lear Jet during the fall of 2003.

4. INSTRUMENT CAPABILITY

Extinction is the HSRL measurement of greatest interest for validation of passive satellite retrievals and for use by the climate modeling community. In Figure 2, we show the accuracy with which the airborne HSRL can measure extinction in the boundary layer under low aerosol loading conditions. In the figure, the solid lines are the true profile of backscatter and extinction used as simulation inputs. The retrieved parameters are shown as individual data points with error bars. (The error bars on the retrieved backscatter are too small to extend beyond the point markers.) For aerosol extinction as weak as 0.05 km^{-1}, the relative error in the extinction measurement is less than 20%. The relative error in the retrieval will decrease with increasing extinction and/or spatial averaging.

Another capability of the HSRL instrument that we intend to exploit is the measurement of *S*. The spaceborne lidar on the CALIPSO satellite and the GLAS instrument on the ICESAT satellite will provide global measurements of attenuated backscatter (the product of the backscatter at an altitude and the two-way transmission from top of the atmosphere to that altitude). These attenuated backscatter measurements will be used to infer extinction and optical depth using retrievals that often rely on assumed values of *S*. For CALIPSO, the greatest uncertainty in the optical depth and extinction data products is due to the uncertainty in *S*. Scientists involved with both missions are studying the sparse existing database of *S* measurements to develop algorithms to estimate the most likely value of *S* based on location and altitude along the orbit tracks of the respective satellites. Routine flights with the airborne HSRL instrument would make a significant contribution to our knowledge of the variability of *S* and its correlation with geographic location, altitude, and season. HSRL will also provide information on the correlation of *S* with CALIPSO lidar observables, such as depolarization ratio and the ratio of 532 and 1064 nm backscatter. These correlations will be used to improve the CALIPSO algorithms used to estimate *S* and thereby increase the accuracy of the CALIPSO extinction and optical depth data products.

Another benefit of the measurement of *S* is that it provides information related to aerosol particle type. Figure 3 shows a simulated retrieval of *S* for a boundary layer consisting of two layers of different particle composition. For this case, we simulated a layer of aerosol with a high black carbon content lofted above a layer of continental aerosol with low black carbon content. Although the backscatter profile used for the simulation input does not provide any indication of the two-layer system, the large change in *S* at the top of the profile clearly indicates a change in particle properties. Using HSRL profiles of *S* along with profiles of depolarization ratio and the ratio of 532 to 1064 nm backscatter, we will be able to discriminate layers of different particle type and constrain inferences on particle composition, especially for black carbon aerosols, which exhibit high *S*.

The vertically resolved information that HSRL provides on particle type and extinction will be useful for comparing to the predictions of chemical transport models (CTMs). Advanced CTMs[7] are designed to assimilate 2-D aerosol products from passive satellite sensors such as TOMS, MODIS, and OMI. While these data provide a great enhancement, the way the model distributes the aerosol vertically determines the predicted lifetime, chemical, and radiative effects of the aerosols. For instance, the lifetime of aerosols can be less than 10 days at the surface and greater than 50 days above 5 km, and lifetimes can differ for soot and sulfate. Airborne HSRL profiles of extinction, *S*, depolarization ratio, and the ratio of 532 to 1064 nm backscatter can be compared with CTM predictions of aerosol transport and evolution on a layer-by-layer basis and should therefore prove to be very useful for validating and improving the models.

5. CONCLUSION

The airborne HSRL system under development at NASA Langley will be a valuable tool for validating spaceborne measurements of aerosol and cloud extinction. It will also be extremely useful for characterizing *S* under various conditions and improving algorithms used to estimate *S* for CALIPSO spaceborne lidar retrievals. Additionally, the combination of profile measurements of extinction, *S*, depolarization ratio, and the ratio of 532 to 1064 nm backscatter should be useful for validating and improving the predictive capability of chemical transport models.

6. REFERENCES

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