THE NASA LANGLEY AIRBORNE HIGH SPECTRAL RESOLUTION LIDAR FOR MEASUREMENTS OF AEROSOLS AND CLOUDS

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ABSTRACT

NASA Langley Research Center (LaRC) recently developed the LaRC Airborne High Spectral Resolution Lidar (HSRL) to make measurements of aerosol and cloud distribution and optical properties. This paper summarizes the design of this lidar and presents some preliminary results from the Megacity Initiative: Local and Global Research Observations (MILAGRO) field mission conducted in Mexico in March 2006.

1 INTRODUCTION

It has long been recognized that more information is needed on the distribution and optical properties of aerosols and clouds. Aerosols play a key role in the processes that govern climate through both direct forcing, via reflection and absorption of solar radiation, and indirect forcing, via altering the formation and albedo of clouds and precipitation. Uncertainties in the magnitude of aerosol forcing of climate are the largest among all known climate forcings. Aerosols also have a large impact on air quality and chemistry in the troposphere. Clouds play a huge role in determining the Earth's climate, and our limited understanding of cloud-climate feedback processes leads to very large uncertainties in our ability to predict climate. Better information is needed on cloud optical properties and vertical distribution to develop improved cloud models for inclusion in climate models. Lidar is widely recognized as a necessary component in any strategy to provide the information on aerosol and cloud spatial distribution and optical properties needed to address these outstanding issues.

The Airborne HSRL project was conceived with the goal to develop a compact, robust nadir-viewing airborne HSRL that could be employed on a variety of important aerosol and cloud related objectives, including providing accurate quantitative measurements of aerosol and cloud properties in the context of radiation- and chemistry-focused field missions, validating the CALIOP lidar on the CALIPSO satellite, and investigating technologies and science benefits of a future spaceborne HSRL instrument. The project was initiated in spring of 2000 and completed in November 2004 when the first ground tests were conducted. The instrument was flown for the first time in December of 2004 on a Lear 25C operated by L3 Communications Flight International Aviation LLC. The instrument performed flawlessly in both ground test and the initial test flights. The system was later reconfigured for deployment on the NASA LaRC King Air B-200 aircraft along with two other remote sensing instruments, the Langley Airborne A-band Spectrometer (LAABS) and the HyperSpectral Polarimeter for Aerosol Retrievals (HySPAR). The goal for deployment of the additional instruments was to enable investigation of new remote sensing strategies involving combined active-passive retrievals, i.e., using HSRL extinction and backscatter data to constrain oxygen A-band and photo-polarimeter retrievals of aerosol optical and microphysical properties.

In March of 2006, the B-200 equipped with the Airborne HSRL, LAABS, and HySPAR was deployed to Veracruz, Mexico, for MILAGRO field mission. This mission involved five other aircraft: the the DOE G-1, NSF C-130, NASA DC-8, the Sky Research J31 (deployed by NASA Ames), and the US Forrest Service Twin Otter. The mission also involved three extensively instrumented ground sites and three additional ground sites with hosting Cimel sun photometers. The major objective of the MILAGRO mission was to investigate the evolution and transport of pollution from a tropical megacity – in this case Mexico City.

This paper provides a discussion of the HSRL technique, an overview of the design of the LaRC Airborne HSRL instrument, and examples of preliminary HSRL observations from the MILAGRO field mission.

2 HSRL TECHNIQUE

Standard backscatter lidars are commonly used to derive aerosol backscatter and extinction. However, a standard backscatter lidar actually measures *attenuated backscatter*: i.e., the product of the backscatter and the two-way transmission of the atmospheric volume between the lidar and the backscatter volume in question. The retrieval of both particulate extinction and backscatter relies on an assumption of their ratio, S [*Klett*, 1981; *Fernald*, 1984]. Error in the assumed value of S creates errors in both the backscatter and extinction profiles. The actual value of S depends on particle composition, size distribution and shape. The

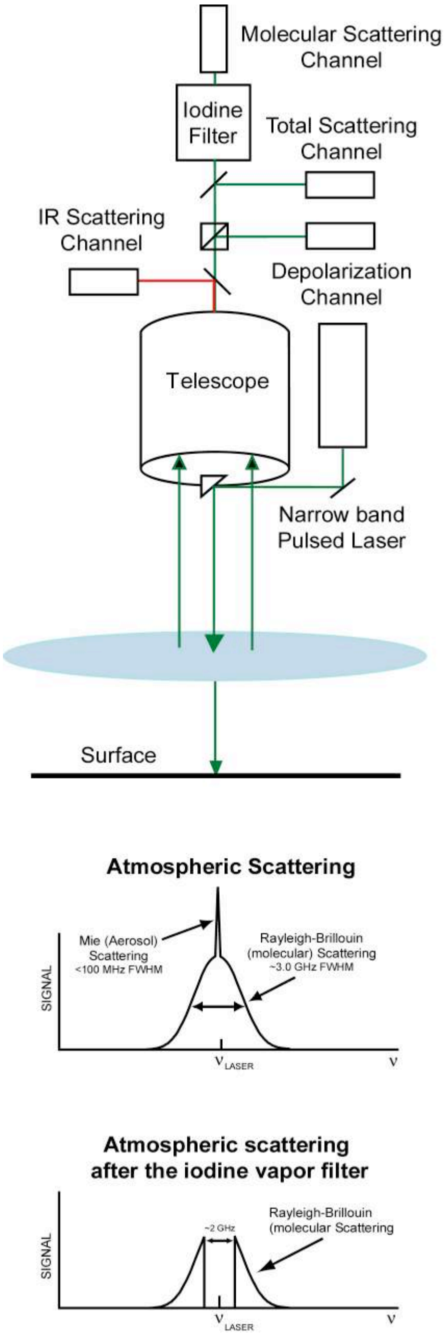

Fig. 1. Block diagram for an HSRL system and return spectra.

value of S for aerosols, S_a, can vary widely ($10 < S_a < 110$) [e.g., *Ferrare et al.*, 2001] and unfortunately is not well known. The HSRL technique [*Shipley et al.*, 1983; *Grund and Eloranta*, 1991; *She et al.*, 1992; *Krueger et al.*, 1993] takes advantage of the spectral distribution of the lidar return signal to discriminate aerosol returns from molecular returns and thereby measure aerosol extinction and backscatter independently. Lidar backscatter from air molecules is Doppler broadened by a few GHz due to the high-velocity random thermal motion of the molecules. The Doppler broadening of backscatter from aerosols is only of the order of a few tens of MHz, however, due to the fact that aerosol particles are much heavier and the velocities of their random thermal motions are significantly lower. Discrimination between aerosol and molecular returns in the Airborne HSRL receiver is accomplished by splitting the returned signal into two optical channels: one with an extremely narrow-band iodine vapor (I_2) absorption filter to eliminate the aerosol returns (the molecular channel) yet passing the wings of the molecular spectrum (see Fig. 1, bottom panel), and another that passes all frequencies of the returned signal (the total scatter channel).

After appropriate internal calibration of the sensitivities of the two channels, the signals are used to derive profiles of extinction, backscatter, and extinction-to-backscatter ratio, S_a. The molecular channel signal is first corrected for the amount of molecular scatter blocked by the I_2 filter. Extinction is then computed from the molecular signal channel by comparing the measured attenuated molecular backscatter profile, which is attenuated by aerosol and molecular extinction along the transmit-receive path, to a reference molecular profile (determined from sonde data or an assimilation model) for which molecular component of extinction can be accurately modeled [*Shipley, et al.*, 1983]. The aerosol backscatter coefficient is computed by taking the ratio between the total scatter signal and the corrected molecular channel signal, and then normalizing by the model molecular backscatter cross section. The profile of S_a is computed from the ratio of the aerosol extinction and backscatter profiles.

3 INSTRUMENT DESCRIPTION

Table 1 lists the major instrument parameters for the Airborne HSRL instrument. The transmitter and receiver occupies a volume roughly 34 in. tall by 22 in. wide by 30 in. deep, and the data acquisition and control system occupies another 13 cubic feet. The laser is injection-seeded using a tunable CW single-mode source laser. The receiver employs a 16-in (40-cm) diameter telescope. To minimize background noise due to scattered sunlight, the field of view is limited to 1 mrad and an etalon filter is used in conjunction with wider bandwidth interference filters for the 532-nm channels. The etalon, similar to those developed for the CALIPSO spaceborne lidar, are temperature tuned and are built by Coronado.

Table 1. System parameters for the airborne HSRL

Transmitter	
Repetition Rate	200 Hz
532 nm energy	2.5 mJ
1064 nm energy	1.0 mJ
Optical Receiver	
Telescope	0.4 m diameter
532 etalon FWHM	40 pm
1064 IF FWHM	0.4 nm
Detection Electronics	
532 nm	PMT, analog detection
1064 nm	APD with analog detection

The key to successful operation as a high spectral resolution lidar is spectral purity and wavelength stability of the laser. The engineering team at LaRC has developed a robust feedback and control system that insures the laser remains locked to the center of an iodine line and have verified that the spectral purity of the laser exceeds our requirements (the measured spectral purity is better than 10^4:1 where the ratio indicates the relative values of the energy in a single longitudinal mode of the laser to the energy outside that mode). The iodine filter transmission at line center was measured to be less than 10^{-6} and the molecular transmission is approximately 30% for an atmospheric temperature of 275K.

Another feature of the system that was found extremely useful for aircraft field work is the active boresight system. An autonomous, real-time boresight control loop continuously monitors the transmitter-to-receiver alignment and tilts a mirror in the transmitter path as required to maintain alignment.

The HSRL also functions as a standard backscatter lidar at 1064 nm, enabling the calculation of the backscatter color ratio (β_{1064}/β_{532}). In addition, the lidar is polarization-sensitive at both wavelengths (i.e., it measures the degree to which the backscatter light is depolarized from the linear polarized state of the transmitted pulses), enabling discrimination between spherical and nonspherical scatterers.

The opto-mechanical system is designed to be compact enough for future deployment on unmanned aerial vehicles (UAVs) or high-altitude aircraft such as the NASA ER-2 and WB-57. The LaRC team has funding over the next three years to add HSRL capability at 355 nm and ozone DIAL measurements at 290 and 300 nm. A new transmitter system involving a ring-architecture Nd:YAG laser and optical parametric oscillators will be developed along with the appropriate receiver components. Provisions for the addition of UV channel pickoffs have been included in the current receiver.

4 PRELIMINARY RESULTS FROM MILAGRO

Fig. 2 shows some preliminary data from the 28 March flight of the MILAGRO field mission. The black line shows the profile of extinction measured with the Airborne HSRL over the Gulf of Mexico east of Veracruz. The blue curve is the *observed* extinction-to-backscatter ratio (S_a) which was computed from the ratio of the independently measured extinction and backscatter profiles for values limited to aerosol backscatter ratios greater than 0.2. The vertical resolution of the data is 300 m. S_a is an *intensive* observable: it depends only on the type of aerosol present not the amount. The S_a profile shown here indicates that the layers evident in the extinction profile are not all of the same type: the top layer having the highest S_a, the layers at 1.5 and 2.5 km with an intermediate S_a, and the lower layer with the lowest S_a.

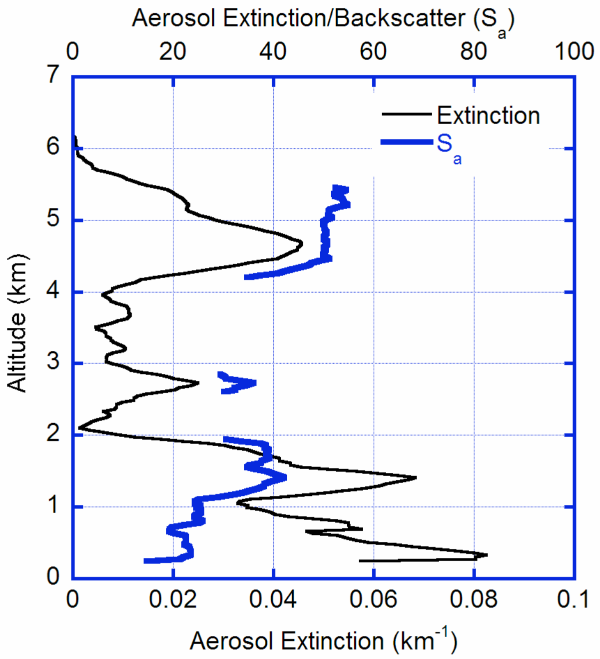

Fig. 2. Extinction and extinction-to-backscatter ratio measurements (60 sec., 300 m vertical resolution) from the 28 March flight conducted over the Gulf of Mexico.

The lower layer is assumed to be a sea-salt dominated maritime layer. Based on consistency with S_a observed over and in the vicinity of Mexico City, layers with the intermediate values are at present assumed to be pollution aerosol. The upper layer, with its relatively high S_a may be biomass smoke from one or more of the many fires that were observed in the region at the time of the experiment. While our present notions of the aerosol types represented in the figure are preliminary, future back-trajectory, model analyses, and comparisons with in situ measurements acquired during a coincident vertical spiral maneuver by the C-130 will be used to confirm the association these S_a

values with particular aerosol types. Fig. 3 shows data acquired on the 13 March flight. The objective of this flight was to map the distribution and optical properties of aerosol over Mexico City and the regions north and south of the city. The data over Mexico City were acquired coincident with a Terra satellite overpass and will be used to assess aerosol retrievals from MODIS and MISR. The top panel shows the flight track originating and terminating in Veracruz. The flight track is color coded with the aerosol optical depth derived from the integral of the HSRL extinction measurement. The middle panel shows the aerosol scattering ratio (the ratio of aerosol backscatter to molecular backscatter) and the bottom panel shows the measured extinction. The B-200 took off at 10:25 local time and landed at 2:10 local time. By the time the aircraft arrived in Mexico City area (~11:10 local time) the boundary layer was beginning to rise in altitude due to solar heating. Points along the flight track that were flown at different times showed dramatic differences in boundary layer structure that occurred over the course of the course of the ~2.5 hour circuit over the Mexico City region.

Along with more detail on the instrument design and configuration, our presentation will provide more examples of data acquired on MILAGRO, including comparisons with coincident extinction measurements made by instruments on other aircraft.

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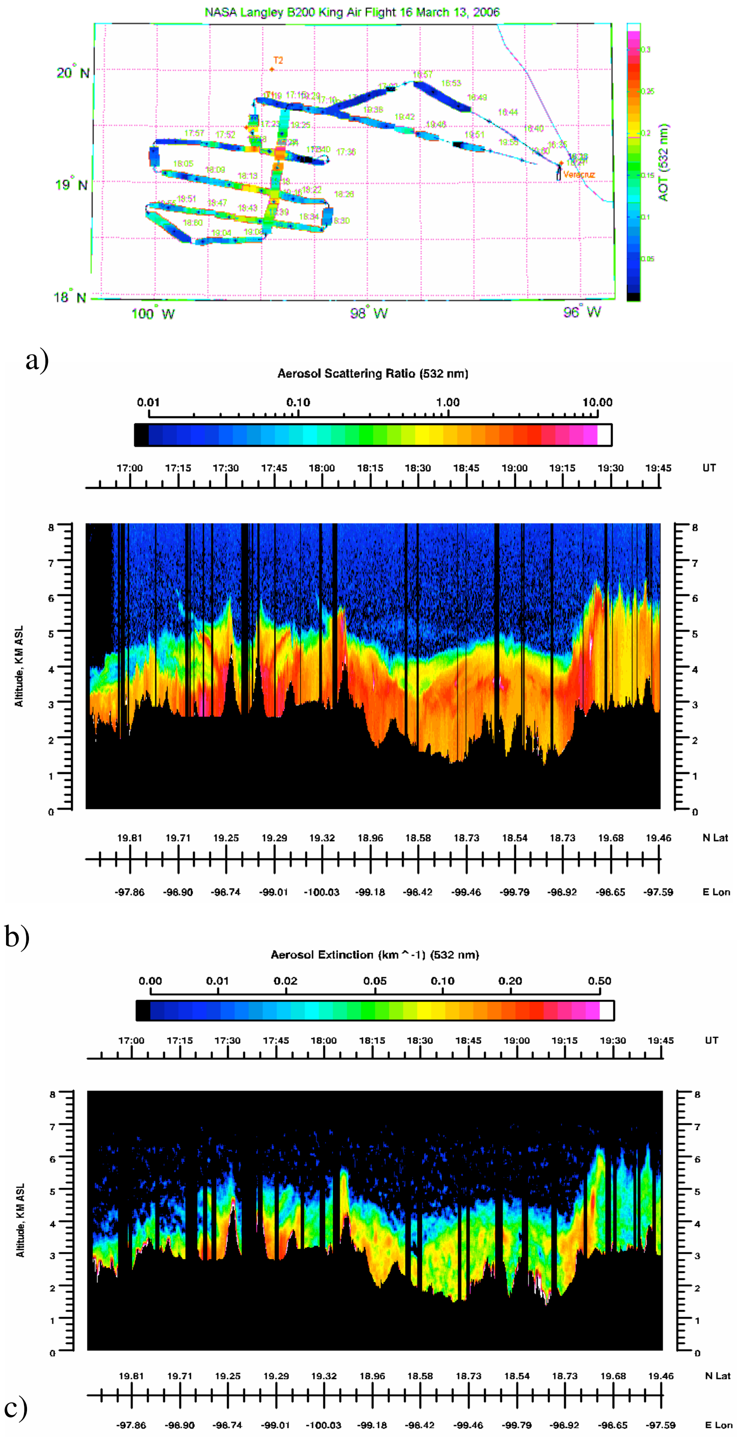

Fig. 3. Figure 3. Data from the 13 March flight of the LaRC Airborne HSRL. a) Flight track above the Mexico City Basin with the AOT color coded over the track, b) ratio of aerosol backscatter to molecular backscatter coefficient, c) aerosol extinction coefficient.