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NASA Future Spaceborne Lidars

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Introduction

NASA Langley Research Center (LaRC) has played a lead role in developing lidar systems and technologies for the measurement of atmospheric aerosols, clouds, ozone, and water vapor during the past 30 years. In 1994 NASA LaRC demonstrated the operation of the Lidar in-space technology experiment (LITE) from the space shuttle (Winker et al., 1996). NASA is now planning to operate an aerosol backscatter lidar as part of the PICASSO-CENA (pathfinder instrument for cloud and aerosol spaceborne observations - climatologie etendue des nuages et des aerosols) satellite mission to study the impact of aerosols on climate (McCormick and Winker, 1998). NASA LaRC has also been developing state-of-the-art Differential Absorption Lidar (DIAL) systems for process studies related to the distribution of ozone, water vapor, aerosols, and clouds. These systems have participated in many major international field experiments around the world. Concerted efforts are in progress to advance lidar technology to enable the deployment of spaceborne DIAL systems that would provide global distributions of ozone, water vapor and other minor species, aerosols, and clouds.

Ozone is a minor atmospheric species that is involved in important chemical and radiative processes in the atmosphere. NASA's Post-2002 Mission Planning Workshop (Kennel et al., 1998) recommended that NASA pursue the development of spaceborne active remote sensors for profiling tropospheric ozone. A strong technology development program was envisioned to be needed for the development of a spaceborne DIAL system for ozone measurement. NASA LaRC and the Canadian Space Agency have jointly been conducting a study concerning the development of a spaceborne DIAL system for the measurement of ozone, aerosol, and cloud distributions (Browell, et al., 1997; Stadler et al., 1998).

Water vapor is a key atmospheric minor species that has a significant impact on climate, atmospheric transport, meteorology, and atmospheric chemistry. The first autonomously operating DIAL system called the Lidar Atmospheric Sensing Experiment (LASE) was developed at NASA LaRC as a precursor to the development of a spaceborne DIAL lidar. In this paper: the heritage of DIAL development and measurements at NASA LaRC are reviewed, the technology needed for spaceborne DIAL is discussed, and the feasibility of ozone and water vapor profile measurements from space is presented.

NASA LaRC DIAL heritage

NASA LaRC has developed airborne, mutiwavelength UV DIAL systems and used them in conducting experiments over different regions of the world during the past 20 years (Browell, 1998). These systems use Nd:YAG pumped dye lasers that operate in the 285-310 nm region for DIAL ozone measurements, and they also simultaneously transmit pulses at 600 and 1064 nm wavelengths for aerosol backscatter measurements. The on- and off-line DIAL laser pulses are transmitted within about 300 □s so that the same scattering volume of air is sampled by the system. All the laser wavelengths are transmitted simultaneously in the nadir and zenith directions to measure ozone and aerosol profiles from the ground to the lower stratosphere. Airborne UV DIAL systems have been operated from the NASA Electra, P-3 and DC-8 aircraft, and they have been flown on over 20 major field experiments with the majority of them having been conducted outside the continental US. A list of these field experiments is given in Table 1. These experiments have been conducted over most of the major geographical regions of the world to understand atmospheric processes in the troposphere and stratosphere including atmospheric chemistry, convection and boundary layer studies, biomass burning and transport of anthropogenic pollution, stratosphere-troposphere exchange, transport of volcanic emissions in the stratosphere, polar vortex dynamics, and Arctic and Antarctic ozone loss. Examples of unique measurements made during a few of these field experiments will be presented in this paper.

Table 1. Airborne UV DIAL Major Field Experiments

	Field Experiment	Base Location
1980	Persistent Elevated Pollution Episode (PEPE)	Wallops, Virginia
1981	North America Plume Study - I	San Juan, Puerto Rico
1981	Cloud Transport Study	Wallops, Virginia
1982	North American Plume Study - II	Bermuda
1984	Tropopause Fold Experiment (TFE)	Las Vegas, Nevada
1984	Atlantic Boundary Layer (BL) Exper. (ABLE-1)	Barbados
1985	Amazon BL Exper. - Dry Season (ABLE-2A)	Manaus, Brazil
1987	Amazon BL Exper. - Wet Season (ABLE-2B)	Manaus, Brazil
1987	Airborne Antarctic Ozone Exper. (AAOE)	Punta Arenas, Chile
1988	Arctic BL Exper. (ABLE-3A)	Barrow & Bethel, Alaska
1989	Airborne Arctic Stratospheric Exped. (AASE-I)	Stavanger, Norway
1990	Arctic BL Exper. (ABLE-3B)	Hudson Bay, Canada
1991	Pacific Explor. Mission-Summer (PEM-West A)	Tokyo; Hong Kong; Guam
1992	AASE-II	Stavanger, Norway
1992	Trans. & Atmos. Chem. Near Equator (Trace-A)	Brazil; S. Africa; Namibia
1994	PEM-Spring (PEM-West-B)	Guam; Hong Kong; Tokyo
1995-6	Tropical/Vortex Ozone Trans. Exp. (TOTE/VOTE)	Hawaii; Alaska; Iceland
1997	PEM Tropics - Summer (PEM-Tropics A)	Tahiti; Fiji; Easter Is.
1998	Atmos. Impact of Subsonic Aircraft (SONEX)	Bangor, Maine; Ireland
1999	PEM Tropics - Winter (PEM Tropics B)	Hawaii; Fiji; Tahiti; Easter Is.

Airborne DIAL water vapor measurements were first made by the NASA LaRC in 1981 (Browell, 1983), and a state-of-the art Alexandrite-laser-based water vapor system was demonstrated from the aircraft in 1990 (Higdon et al, 1994). In addition, the LASE system was developed with the twin objectives of demonstrating autonomous operation of a narrowband DIAL system from a high altitude ER-2 aircraft and acquiring a high quality instrument for measuring high resolution profiles of atmospheric water vapor and aerosols over the entire troposphere. LASE was developed and demonstrated to meet precise engineering performance specifications (Moore et al., 1996). The LASE system operates in the 815-nm band of water vapor and uses a double pulsed Ti:sapphire laser that is frequency locked to a water vapor line. Water vapor over the entire troposphere is measured by electronically tuning the on-line to operate at any specified spectral location on the water vapor absorption line profile. LASE was operated, autonomously, from the NASA ER-2 aircraft during several field experiments from 1994 to 1996. It has also been reconfigured and flown on the NASA P-3 and DC-8 aircraft. LASE has demonstrated the capability to measure water vapor over the entire troposphere with an accuracy of 6% or 0.01 g/kg (Browell et al., 1996). LASE has participated in five major field experiments during 1995-1999, and a list of these field experiments is given in Table 2. During these field experiments LASE has been used to study boundary-layer development, convective outflow, hurricane development, tropical tropospheric chemistry, stratosphere-troposphere exchange, and aerosol radiative forcing study experiments. Examples of unique LASE measurements will be given in this presentation.

Table 2. LASE Field Experiments

Year	Experiment	Location	Study Objective
1995	LASE Validation Experiment	Wallops Island, Virginia	Validation of LASE
1996	Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX)	Wallops Island, Virginia	Urbane Haze layers
1997	Southern Great Plains (SGP97) Experiment	Oklahoma City, Oklahoma	Boundary Layer Development
1998	Convection and Moisture Experiment 3 (CAMEX-3)	Cocoa Beach, Florida	Hurricane development
1999	Pacific Exploratory Mission B	Hawaii, Fiji, Tahiti	Tropical Chemistry

Future Spaceborne DIAL systems

a) Ozone and aerosol DIAL system

A spaceborne DIAL system will provide high resolution ozone and aerosol profiles in the troposphere, a capability that is not available from the current or planned spaceborne passive remote sensors. A spaceborne DIAL system would be instrumental in addressing a number of atmospheric science studies related to atmospheric chemistry, atmospheric pollution and transport, atmospheric dynamics including convection and stratosphere-troposphere exchange, radiation budget and climate. The technology challenges for a spaceborne ozone DIAL system are in the areas of both transmitter and receiver subsystems. Compared to an airborne DIAL system that operates at a nominal altitude of about 10 km, the intensity of atmospheric signals, from near the ground, received at a spaceborne DIAL system at an altitude of 400 km will be at least a factor of 1600 lower! To compensate for this reduction of signal, the spaceborne DIAL system will require high powered tunable UV lasers and large collection area receivers (Browell et al., 1997; Stardler et al., 1998). In addition, more data averaging will be needed than the state-of-the-art airborne lidar systems in order to improve the signal-to-noise ratio of spaceborne measurements.

Table 3. Spaceborne O_3/Aerosol DIAL Parameters

Wavelength (on/off)	308/320 nm (Ozone) 524/960 nm (Aerosol/Clouds)
Laser Energy	500 mJ
Rep. Rate	10 Hz (Pulse Pairs)
S/C Altitude	400 km
Receiver Diameter	2 m
Opt. Efficiency	50 %
Quantum Efficiency	25% (Analog/Photon Counting)

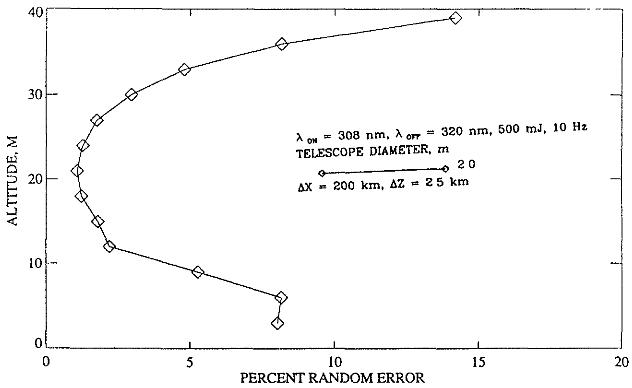

Figure 1. Spaceborne O_3 measurement error

Another important consideration for a spaceborne ozone DIAL system is the selection of on- and off-line wavelengths. An on-line wavelength of 308 +/- 2 nm and an off-line separated by 10 to 12 nm higher is required to be able to penetrate the strongly absorbing stratospheric layer, optimize the performance for tropospheric measurements, and reduce systematic errors. The projected performance of a spaceborne DIAL system, which is based upon the lidar parameters given in Table 3, is shown in Figure 1. A night background condition and the Standard US ozone profile was assumed. Trade-off studies related to the selection of lidar parameters for a spaceborne ozone and aerosol lidar system will be discussed in this presentation.

b) Water vapor and aerosol DIAL system

Over the last two decades NASA LaRC has played a lead role in developing state-of-the-art water vapor DIAL systems, and in defining the scientific objectives and technology requirements for a spaceborne water vapor and aerosol lidar. Demonstration of autonomous LASE operations and measurements during field campaigns have enhanced the maturity of DIAL for space applications. Technology developments are in progress at NASA LaRC to develop simpler, high power, efficient, compact, and light weight tunable laser systems in the 940-nm region (Barnes, 1998) for application to spaceborne DIAL water vapor and aerosol measurements. Operation in the 940-nm band of water vapor is required to enable upper troposphere water vapor measurements from space. Efficient, low noise, and photon counting APD detectors are required to achieve satisfactory signal-to-noise ratios. Ultra narrowband (FWHM ~ 50 pm) filters will be needed for daytime measurements from space. The projected performance of spaceborne DIAL systems (Ismail and Browell, 1989) based upon the lidar parameters in Table 4 is shown in Figure 2. A night background and a mid-latitude summer water vapor profile model have been assumed. A discussion of the sensitivity of the performance to key lidar parameters will be presented along with the need for other useful correlative measurements from space.

Table 4. Spaceborne H_2O/Aerosol DIAL Parameters

Wavelength (on/off)	940 nm
Laser Energy	500 mJ
Rep. Rate	10 Hz (Pulse Pairs)
S/C Altitude	400 km
Receiver Diameter	1 m
Opt. Efficiency	50%
Quantum Efficiency	40% (Low Noise Si:APD)

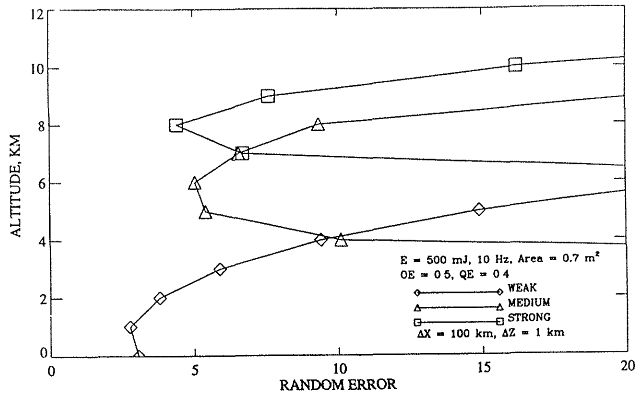

Figure 2. Spaceborne H2O measurement error

Conclusion

NASA LaRC has played a key role in defining the scientific objectives, technology requirements, and technology demonstration of spaceborne lidar systems for atmospheric studies. The maturity of DIAL technique has been demonstrated by developing and conducting field studies around the world using state-of-the-art lidar systems for the measurement of atmospheric ozone, water vapor, aerosols, and clouds. The feasibility of spaceborne DIAL systems will be discussed in this presentation along with the opportunities for their future deployment.

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