LASE Validation Experiment

Edward V. Browell[1], Syed Ismail[1], William M. Hall[1], Alvah S. Moore, Jr.[1], Susan A. Kooi[2], Vincent G. Brackett[2], Marian B. Clayton[2], John D. W. Barrick[1], Frank J. Schmidlin[3], N. Scott Higdon[1], S. Harvey Melfi[4], and David N. Whiteman[3]

[1]NASA Langley Research Center, MS-401A, Hampton, Virginia 23681-0001, USA
E-Mail: e.v.browell@larc.nasa.gov

[2]Science Applications International Corporation, Hampton, Virginia, USA

[3]NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

[4]University of Maryland, Baltimore County, Maryland, USA

Abstract. An extensive validation experiment was conducted in September 1995 from Wallops Island, Virginia, to evaluate the performance of the Lidar Atmospheric Sensing Experiment (LASE) system for the measurement of water vapor profiles under a wide range of atmospheric and solar background conditions. These measurements were compared with many different in situ and remote measurements in the most extensive water vapor intercomparison ever conducted. The LASE water vapor measurements were found to have an accuracy of better than 6% or 0.01 g/kg, whichever is greater, across the entire troposphere.

1 Introduction

Water vapor plays an important role in many atmospheric processes related to radiation, climate change, atmospheric dynamics, meteorology, the global hydrologic cycle, and atmospheric chemistry, and yet our knowledge of the global distribution of water vapor is very limited. The Differential Absorption Lidar (DIAL) technique has been demonstrated to provide needed high resolution water vapor measurements from a medium-altitude aircraft [1,2], and the Lidar Atmospheric Sensing Experiment (LASE) is a key step in developing this capability for a high-altitude aircraft and, ultimately, from space [3,4,5]. The LASE instrument is the first fully engineered, autonomous DIAL system, and it is designed to operate from the ER-2 aircraft and to make water vapor, aerosol, and cloud profile measurements across the troposphere [6]. This system was flown from the NASA Wallops Flight Facility in a series of engineering flights during September 1994 [7] and June 1995. In September 1995, a comprehensive field experiment was conducted to evaluate the water vapor measurements capabilities of LASE under a wide range of solar background and atmospheric conditions. This paper describes the LASE Validation Experiment and presents results of the LASE performance evaluation for water vapor measurements across the troposphere.

2 LASE Validation Experiment

Following the completion of the LASE development and the final engineering flight testing in June 1995 at the NASA Wallops Flight Facility (WFF), LASE was flown in

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a rigorous validation experiment at the WFF over a three week period in September 1995. The objectives of the LASE Validation Experiment were to: 1) operate LASE under a wide variety of atmospheric and solar background conditions, compare its measurements to in situ and remote water vapor measurements, and assess its capability to measure water vapor profiles across the troposphere; 2) conduct LASE flights so that, when possible, scientifically useful data could be obtained for limited case studies of important atmospheric processes; and 3) coordinate LASE flights for the purpose of water vapor intercomparisons between groundbased, airborne, and satellite instruments.

This field experiment brought together the largest collection of different water vapor measuring instruments to be used simultaneously in a water vapor intercomparison experiment. LASE water vapor measurements were compared with in situ measurements from radiosondes, airborne hygrometers onboard two aircraft, and remote lidar measurements from the ground and an airborne platform. The in situ balloon water vapor measurements were made using the Vaisala radiosonde hygrometers launched from the WFF and from near the NASA Langley Research Center (LaRC). In addition, a World Meteorological Organization (WMO) water vapor balloon intercomparison was conducted concurrently with this experiment. In situ water vapor measurements were made on two aircraft that under flew LASE at different altitudes. The NASA Lewis Research Center operated a Lear Jet for in situ water vapor measurements in the 5-12-km altitude range using two chilled mirror hygrometers: General Eastern Model 1011B and Buck CR-1 (cryogenic hygrometer). A WFF C-130 was used below 5 km for in situ water vapor measurements with two chilled mirror hygrometers: General Eastern Model 1011B and EG&G Model 300. The LaRC airborne water vapor DIAL system [2] was operated in a nadir mode from the C-130 to provide remote water vapor and aerosol distributions along the ER-2 flight track for spatial correlation with the LASE measurements. Water vapor profiles from near the ground to about 8 km were obtained at night with the NASA Goddard Space Flight Center (GSFC) Raman lidar system based at WFF [8,9].

Ten flights were made with LASE between September 8-26, 1995, for a total of 60 flight hours for the ER-2. An example of LASE water vapor and aerosol measurements on a long-range flight is shown in Fig. 1. In this case, the measured total atmospheric scattering ratio (aerosol plus molecular scattering divided by molecular scattering) distribution is shown with the water vapor mass mixing ratio (specific humidity) distribution. The water vapor ranges from ~10 g/kg near the surface to $\leq$0.01 g/kg near the tropopause, which varies in altitude from about 14 km on the southern end of the flight leg (left side of figure) to about 11 km on the northern end (right side of figure). To obtain complete tropospheric coverage of the water vapor distribution on one pass of the ER-2, LASE was operated in an alternating mode between strong (line center) and weak (side of strong line [10]) water vapor cross section for the on-line DIAL wavelength. This mode was only implemented near the end of this field experiment after evaluation was done for operation in each absorption region independently. In Fig. 1, the aerosols can be seen to have scattering ratios (total scattering ratio - 1) exceeding 5 near the ground and low values (~0) near the tropopause. Aerosols and water vapor have their source at the surface, and therefore, they tend to be generally positively correlated across the troposphere. Optically thick clouds with tops to 13 km are readily apparent on the south end of the leg and in the center of the leg with tops to 4.5 km. Above the tropopause, the aerosol scattering increased with altitude into the lower stratosphere due to the presence of residual aerosols from the Mount Pinatubo eruption in June 1991. This long-range atmospheric cross section shows an example of the measurement capability of LASE to obtain complete water vapor, aerosol, and cloud distributions covering a broad dynamic range of atmospheric conditions.

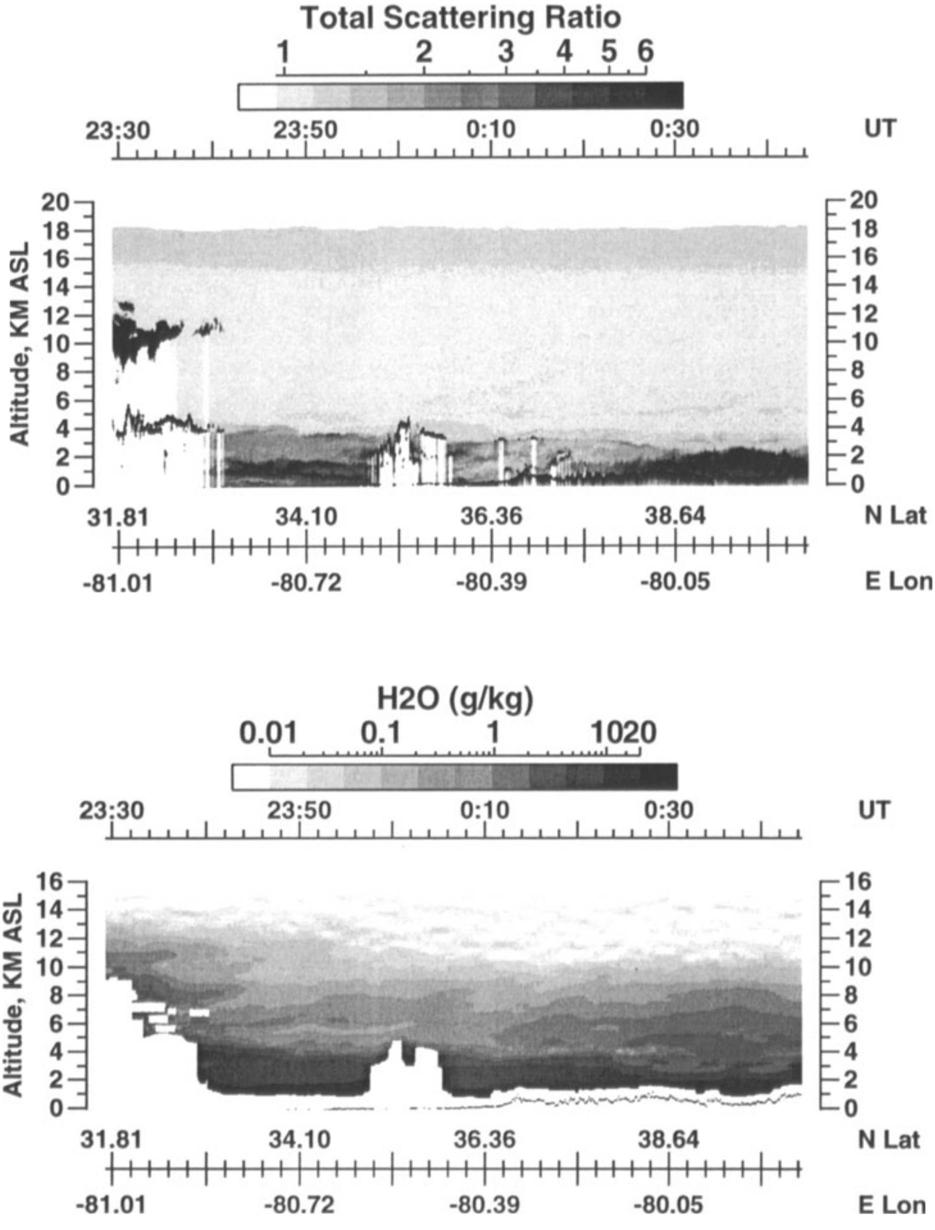

Fig. 1. LASE simultaneous aerosol (top) and water vapor (bottom) distributions obtained on September 26, 1995, on a flight from near Savannah, Georgia to near Charleston, West Virginia.

Most of the flights that were used in quantitatively evaluating the LASE water vapor profile measurements were centered around the WFF. The general plan involved repeated over flights of the balloon and Raman lidar site while LASE was operated on either a strong or weak water vapor absorption. Profile measurements of water vapor were also obtained by the Lear Jet and C-130 in spirals over the same location. In addition, since the LASE DIAL water vapor measurements are vertically and horizontally averaged with a vertical resolution of 330 m when using the weak (side-line) absorption for the lower troposphere and 510 m when using the strong (line center) absorption for the mid to upper troposphere and a horizontal resolution of at least 12 km (1 min), the in situ aircraft were flown along the LASE flight track at a wide range of "constant" altitudes legs. Both aircraft actually flew their flight tracks with a saw-tooth altitude profile about the average prescribed altitude to cover the vertical resolution of the LASE measurement.

An example of a comparison of water vapor profiles is shown in Fig. 2. The ER-2 flew over WFF with LASE first operating on a strong water vapor absorption line which was optimum for making measurements in the altitude range of 7.5-14 km. Later, LASE was retuned to operate on a weak side-line position, and it was flown over WFF again for water vapor measurements in the altitude range of 0-7.5 km. The LASE profiles are from a 2 min average centered over the WFF site, and the increasing noise in each of the LASE profiles at the upper altitude range of each profile is due to the low optical depth in that altitude range for the DIAL water vapor measurement. The combination of the two WFF crossings provided a composite water vapor profile covering the full altitude range from near the surface to the tropopause at 14 km. The LASE measurements compare very well with the in situ

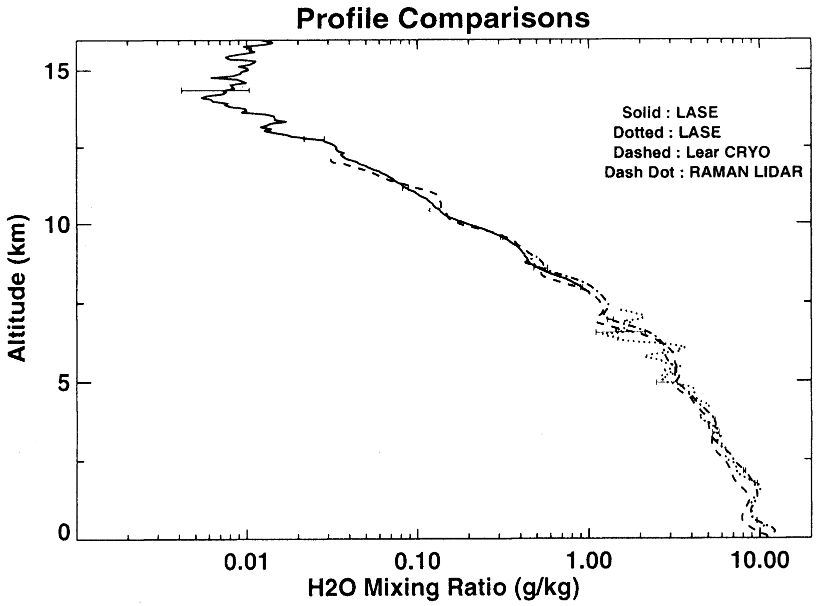

Fig. 2. Comparison of LASE strong-line (solid line) and weak-line (dotted line) water vapor profiles with in situ Lear cryo hygrometer and remote Raman lidar water vapor measurements above the NASA Wallops Flight Facility on the night of September 12, 1995.

cryogenic hygrometer measurements on the Lear Jet over the entire range of the in situ measurements (0-12 km) as well as with the NASA Goddard Space Flight Center Raman lidar measurements from 0-8 km. Many intercomparisons were done throughout this experiment, and the average differences and standard deviations of these differences were determined for each intercomparison. A sample of one of the summary tables for the weak line profile intercomparisons is given in Table 1. Also, indicated in the table is the average difference in the water vapor profiles if a small altitude shift ($\leq$120 m) in the data is needed to line up prominent atmospheric features between the comparison profiles. Small altitude differences can result from relative uncertainties in the geometric altitudes of the ER-2 (known to ~60 m) and the other aircraft and balloons and the Raman lidar measurements. When a shift is indicated, an autocorrelation technique is used to determine the amount of the shift.

The average water vapor profile differences between LASE and the aircraft and balloon measurements are less than 12% (without any altitude adjustments), and the differences with the Raman lidar profiles are less than 4%. Small altitude adjustments improved a couple of the in situ profile comparisons while the average differences with the Raman lidar profiles became slightly larger. Some of the residual differences between the LASE water vapor profiles and the in situ and ground-based remote profile measurements result from the differences in the atmospheric sampling. For the entire field experiment, a total of thirty-nine profile intercomparisons were made when the time difference was less than 30 min. The average of the average profile

Table 1. Comparison of LASE water vapor measurements (weak side-line mode) with in situ and Raman lidar measurements on September 12, 1995.

Instrument Type	Location & Type of Comparison	Inst. Mea. or Launch Times (UT)	LASE Times (UT)	Ave. ΔT^1 (min)	Altitude Range/Ave (km)	H_2O Range/Ave (g/kg)	Ave. ΔH_2O^2 (%)	Std. Dev. ΔH_2O (%)	Alt. Shift[3] (m)	Shifted ΔH_2O^2 (%)
	PROFILES:									
C130-GE1011	WFF	0224-0231	0259-0301	32	1.3-3.2	9.4-4.63	11.9	9.1	—	—
		0459-0513	0453-0455	12	0.4-4.7	11.1-4.12	7.2	4.9	-120	3.6
Vaisala Sonde	WFF	0400	0453-0455	43	0.4-6.0	10.9-2.40	9.4	6.7	—	—
	LaRC	0400	0429-0431	19	0.4-6.6	10.3-2.00	8.7	11.2	-90	5.0
Raman Lidar	WFF	0255-0305	0259-0301	0	0.4-6.5	11.4-2.07	-3.9	12.3	—	—
		0337-0347	0341-0343	0	0.4-6.5	11.0-2.05	-2.9	9.2	-90	-5.2
		0407-0417	0411-0413	0	'0.4-6.6	11.4-2.04	-1.6	10.8	—	—
		0449-0459	0453-0455	0	0.4-6.0	11.6-2.81	-1.5	6.3	-60	-3.0
	LEVEL Legs:									
C130-GE1011	Leg B-C-D-B	0230-0325	0300-0341	24	1.52	9.6	3.8	—	—	—
	Leg D-E	0310-0339	0332-0350	16	1.53	9.4	4.9	—	—	—
	Leg E-D	0345-0419	0402-0424	11	0.43	10.2	4.9	—	—	—
	Leg B-D-C-B	0404-0501	0412-0454	4	0.43	10.6	1.3	—	—	—

[1] Average time difference between measurements (assumes 5 m/s sonde ascent to center of altitude range);
[2] ΔH_2O =(LASE H_2O-Inst. H_2O)/Inst. H_2O; [3] Altitude shift of LASE data to make features match; [4] g/kg.

differences was less than 2% (with or without shifts), and the standard deviation of the differences was less than 10% without any shifts and less than 7% with a few shifts.

To better account for the horizontal variability of the atmosphere, the in situ aircraft were flown along the LASE flight track at several different "constant" altitudes. An example of these intercomparisons is shown in Fig. 3. The average and standard deviation of the water vapor measurements made by the aircraft instruments and the average and standard error of the LASE water vapor profile over the same flight track is shown. The agreement is excellent even down to water vapor values as low as 0.026 g/kg. The intercomparisons for the weak side-line measurements are given in the second part of Table 1. Even without any altitude shift, the agreement is better than 5%. Similar results for daytime comparisons were obtained for both strong line and weak side-line operation. During this field experiment, there were twenty-six "constant" altitude comparisons made with less than 30-min separation. The average of the differences of those comparisons was 1.3%, and a standard deviation of the differences was 4.6%. In total, sixty-five comparisons (profiles and "constant" altitude legs) were made for an average difference of 1.6% and a standard deviation of 6.0%.

During this field experiment, various atmospheric case studies were conducted that would be suitable for validating LASE and that would take advantage of the unique LASE measurement capabilities. These included studies of hurricane structure, sea

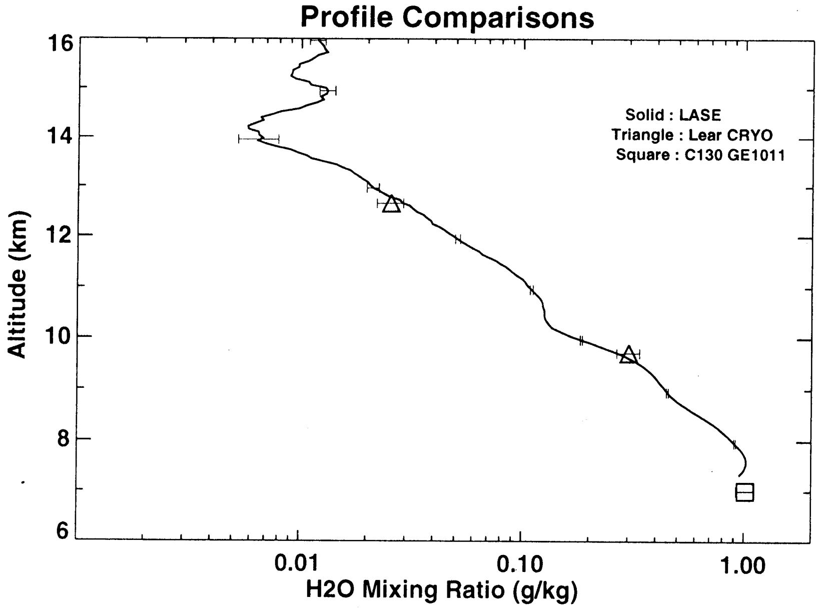

Fig. 3. Comparison of LASE strong-line water vapor profile with in situ airborne water vapor measurements along the same flight track on the night of September 12, 1995.

breeze development, water vapor flux from land and ocean, frontal structure, cirrus cloud formation, and stratosphere-troposphere exchange. In addition, various data sets were obtained with this system for comparison with airborne and spaceborne passive water vapor instruments.

3 Conclusions

The September 1995 LASE Validation Experiment provided a comprehensive set of in situ and remote water vapor measurements for comparison with the remote water vapor profile measurements made by LASE. The LASE water vapor measurements were found to have an absolute accuracy of better than 6% or 0.01 g/kg, whichever is greater, across the entire troposphere. This field experiment demonstrated that this system is capable of making water vapor, aerosol, and cloud measurements with high spatial resolution under a wide range of atmospheric and solar background conditions. LASE performed reliably during an intensive flight schedule of 10 flights in 19 days, and it obtained unique data on important atmospheric case studies. This field experiment completes the development and evaluation of LASE. The demonstration of an autonomously operating water vapor DIAL system represents an important step in the development of a future spaceborne water vapor DIAL system.

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