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Airborne and Ground-based Measurements Using a
High-Performance Raman Lidar. Part II: Ground-based.

Popular Summary

The same RASL hardware as described in part I was installed in a ground-based mobile trailer and used in a water vapor lidar intercomparison campaign, hosted at Table Mountain, CA, under the auspices of the Network for the Detection of Atmospheric Composition Change (NDACC). The converted RASL hardware demonstrated high sensitivity to lower stratospheric water vapor indicating that profiling water vapor at those altitudes with sufficient accuracy to monitor climate change is possible. The measurements from Table Mountain also were used to explain the reason, and correct, for sub-optimal airborne aerosol extinction performance during the flight campaign.

Airborne and Ground-based Measurements Using a High-Performance Raman Lidar. Part II: Ground-based

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1 Abstract

The performance of the airborne Raman lidar called RASL during the WAVES_2007 field campaign in the summer of 2007 was described in part I of this paper. Following this campaign, RASL was installed in a mobile trailer for ground-based use during the MOHAVE-II field campaign held in October, 2007 at Table Mountain Facility in southern California. This ground-based configuration of the lidar hardware is called ALVICE. During the MOHAVE-II field campaign, ALVICE demonstrated significant

sensitivity to lower stratospheric water vapor. Comparisons with Cryogenic Frostpoint Hygrometer, which were launched on balloons during the campaign for in-situ validation of the lidar measurements, agreed within $\pm 10\%$. Numerical simulations were used both to 1) verify that a Raman lidar system with the configuration of ALVICE could be expected to operate usefully into the lower stratosphere and 2) determine that the Raman nitrogen signal strength was reduced by approximately a factor of 10 during the WAVES_2007 flight campaign thus explaining the sub-optimal aerosol extinction performance during that mission. Optimization considerations are presented for Raman water vapor lidars that are intended for measurements extending into the lower stratosphere.

2 Introduction

The Network for the Detection of Atmospheric Composition Change (NDACC) has recently established long term monitoring of water vapor using Raman lidar as one of its core objectives [Leblanc and McDermid, 2009]. Some of the major activities undertaken to address this objective have occurred at the Table Mountain Facility (TMF) of the Jet Propulsion Laboratories where a large power aperture Raman lidar system has been developed for monitoring water vapor mixing ratio in the upper troposphere and lower stratosphere. A coordinated part of this NDACC effort has been the hosting of 2 intensive field campaigns at the TMF location in 2006 and 2007. These campaigns have been called Measurements of Humidity And Validation Experiments (MOHAVE)

[Leblanc andMcDermid,2009]. Aground-basedversion oftheRamanAirborneSpec-troscopicLidar(RASL)that wasdescribedinpartI ofthispaper wasdeployedin a mobile trailer for the second of these MOHAVE campaigns held in October, 2007. Here in part II of this paper, we will describe the ALVICE water vapor mixing ratio performance demonstrated during that campaign and analysis based on those operations. These results indicate that a Raman lidar system with the specifications of ALVICE can usefully probe lower stratospheric water vapor and offer an explanation for the sub-optimal aerosol extinction performance of RASL during the WAVES_2007 campaign.

3 ALVICEOperationsDuring MOHAVE_2007

TheAtmosphericLidarforValidation,InteragencyCollaboration andEducation(ALVICE) wasdeployed toTableMountain,CAfor theMOHAVE_2007 campaignin earlyOcto-ber,2007. Atthattime,thehardware configuration ofALVICEwas essentiallyidentical tothat of theRASL systemthat wasdescribedinpartI.The maindifferencefromthe hardware configuration showninTable1ofpartI and the configuration ofALVICEfor the MOHAVE_2007 campaign was that a seeded version of the Continuum9050laser wasused forthemoHAVE campaign.

3.1 Instrument setup and optimization

At the beginning of the MOHAVE campaign, experiments were performed on the ALVICE hardware in order to optimize the performance of the system. These experi-

ments involved spectrally adjusting (by mechanically tilting) the central wavelength of the Raman N2 filter to maximize signal throughput, installing a reflective blocker in the system to reduce the magnitude of the 355 nm signal that is transmitted to the Raman channels and adjusting the x5 laser beam expander to maximize far field signal. Each of these will be briefly described.

3.1.1 Optimizing the Raman N2 filter

The N2 interference filter used for both the airborne RASL measurements from part I and the ground-based ALVICE measurements described here was developed under a NASA Advanced Component Technology (ACT) research effort involving Barr Associates and our Raman lidar group [Whiteman et. al, 2007]. One of the interference filters produced during that research was specifically designed to maximize the performance of the Raman N2 measurement and possessed a 0.1 nm FWHM and ~60% peak transmission. The central wavelength was specified to be ~0.1 nm longer than the center of the Raman N2 q-branch when excited by a tripled Nd:YAG laser (~386.7 nm). Specifying the filter with a longer wavelength permits the filter to be tilt-tuned to align the transmission peak of the filter with the Raman return signal. The Raman N2 q-branch, when excited at 354.7 nm, itself covers approximately 0.07-0.08 nm [Bendsten et. al., 2000] so the use of a filter narrower than 0.1 nm could lead to a significant reduction in signal throughput. Because the width of the filter used here is only ~0.02 nm or so wider than the feature desired to be measured, careful tuning of the transmission peak of the filter is

required. Such tuning was not performed in the airborne measurements described in part I due to a host of higher priority items that were being addressed in those first-flight efforts. The MOHAVE campaign provided good operating conditions for performing this tuning through repeated tilting of the filter and inspection of the return signal strength at far range. The use of a seeded laser simplified the task of maximizing the filter transmission tilt angle since at each candidate tilt angle it was possible to scan the laser output wavelength over a range of ~ 0.03 nm. Proper centering of the filter's transmission peak on the Raman N₂ feature was determined by minimizing the change in received signal strength as a function of change in laser output wavelength. The signal strength achieved in the Raman N₂ channel after these optimizations was compared with the signal strength achieved during the airborne campaign described in part I confirming that the 0.1 nm filter was mistuned by approximately 1.5 degrees during the WAVES_2007 campaign. This mistuning resulted in approximately an order of magnitude reduction in signal strength during the airborne campaign described in part I.

3.1.2 Use of a reflective blocker

Two of the lidar systems used in the first MOHAVE campaign in 2006 [Leblanc and McDermid, 2009] used optical fibers to relay the signal from the prime focus of the telescope to a receiver box that performed the wavelength selection and detection. Fluorescence in these optical fibers was found to contaminate the upper tropospheric water vapor signal even when using

"High-OH" fibers as previously recommended [Sherlock et al., 1999]. In

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fact, after the conclusion of this first MOHAVE campaign further investigations were performed on fiber optics that were specifically obtained from manufacturers to minimize fluorescence. All of the fibers tested indicated the presence of fluorescence of significant magnitude when considered within the context of measuring a weak Raman water vapor signal in the upper troposphere and lower stratosphere (UT/LS). (It is interesting that one of the vendors even stated "I will stake my career on it: this fiber will not fluoresce!").

Although most of the attention was focussed on the presence of fluorescence in optical fibers, there was still concern over the presence of fluorescence in non-fiber coupled lidar systems like ALVICE. For this reason, a custom reflective blocker was obtained from Barr Associates with the goal of minimizing the amount of potentially fluorescence inducing 355 nm light that was transmitted into the Raman section of the ALVICE receiver module. Long duration measurements were made under clear sky conditions to test if the addition of this blocker made a noticeable difference in the far field ALVICE Raman water vapor signal. The results of the tests are shown in figure

1.

The figure shows the mean water vapor signal count rate (signal + background) using a long duration set of measurements on each night. At each altitude shown, the value plotted is the average over an interval that spans ± 5 km from the altitude of the point

shown. For example, the values shown at 25 km is an average over the range of 20 - 30 km. The data acquisition times varied from 2.5 hrs on Oct. 4 to 10 hrs on Oct. 10. A summary of the measurement configuration on each night is as follows:

Date	Blocker installed?	Beam Expander Opti- mized?
Oct. 4 and 6	No	No
Oct. 7 and 8	Yes	No
Oct. 10 (next subsection)	Yes	Yes

The mean countrate at 25 ±5km for the measurements from Oct. 4 and 6 tend to group approximately 1-2 Hz higher than the measurements from Oct. 7 and 8 at the same altitude. At greater altitudes, however, the mean countrates from all 4 nights are in better agreement. The results shown here are consistent with the removal of a small amount of fluorescence in the Raman detector box caused by the received 355 nm radiation. The Oct. 10 measurements are addressed next.

3.1.3 Beam Expander Focusing

Prior to operations on the night of October 10, the x5 laser beam expanding telescope was carefully adjusted for maximize signal in the far-field. A significant increase in the ALV ICE far-field water vapor performance was achieved by this adjustment as can be seen in figure 1. Taking the background countrate to be approximately 27 Hz, the figure shows that the mean signal from water vapor has been increased by approximately 5 Hz at

the 20-30 km level and is now clearly discerned as being above the background.

4 Numerical Simulations

The early ALVICE measurements during MOHAVE, such as those from Oct. 10, indicated significant sensitivity to lower stratospheric water vapor concentration. As the RASL/ALVICE system had been developed for downward-looking airborne use, no work had been done previously in simulating the expected upward-looking performance under the conditions of the MOHAVE campaign. Therefore, one of the early efforts following MOHAVE was to assess through the use of numerical simulation whether one could expect that a Raman lidar system with the performance parameters of ALVICE could be expected to measure lower stratospheric water vapor concentrations. Were real signals truly expected to be measured at altitudes beyond 20 km agl from a location like Table Mountain as indicated in figure 1?

A previously validated numerical model [Whiteman et. al., 2001b] was used to address this question using data acquired on the night of October 14. On this night, two Cryogenic Frostpoint Hygrometer (CFH) systems [Všmel et. al., 2007] were launched on balloons during the period of the ALVICE measurements. The CFH data were used to define the water vapor field that were used as input to the numerical model. All known ALVICE efficiency and configuration parameters were also included in the model. For both the water vapor and nitrogen signal simulations, there was a single

adjustable efficiency parameter that was used in the model so that the simulated data provided a best fit to the real ALVICE data [Whiteman et al., 2001b]. This adjustable parameter accounts for optical efficiencies that are not explicitly provided to the model such as those for telescope and secondary mirror reflectivities, beam splitter and collimating optics transmissions. For this study, a 1-hr summation of ALVICE data that began at the time of the CFH launch was used. The values of the free parameters that provided a best fit to the ALVICE data were 0.3 and 0.9 for the nitrogen and water vapor channels, respectively. These values reflect a design goal for RASL of optimizing the water vapor signal throughput in the system at the expense of the nitrogen signal. It also indicates that there is little room for improvement in the water vapor signal throughput of the system. The results of the simulation comparison are shown in figure 2 where the model results are presented without random noise so that they appear almost to be an average of the real ALVICE data.

There is very good agreement between the combined analog and photon counting data from ALVICE (the "glued" data [Whiteman et al., 2006a]) and the model simulations. A careful inspection of the figure reveals that the signal merges into the background at ~80 km and ~30 km for the nitrogen and water vapor signals, respectively. This model simulation indicates that real signal is present in the ALVICE water vapor data up to ranges of approximately 30 km. The comparison of the actual CFH and ALVICE measurements from October 14 are shown in figure 3 using both 1 hr and 9 hr

summations of ALVICE data. The balloon that carried the CFH aloft burst at an altitude of 19 km. A moving average smoothing was implemented on both lidar profiles using a window-size that increased from 30 meters at the surface to 1.2 km above 12 km. The 1-hr ALVICE profile is displayed to 19 km while the 9-hr average profile extends to 24 km. Atmospheric variability during the 9-hr measurement period degraded the comparison between the CFH and the 9-hr average ALVICE profile. Overall, the ALVICE 1-hr profile and the CFH measurements agree very well with discrepancies remaining generally within $\pm 10\%$ throughout the measurement range.

5 Discussion and Summary

The task of quantifying upper tropospheric and lower stratospheric water vapor with sufficient accuracy to monitor trends in climate is a substantial challenge. Technologies that are candidates for this task in addition to Raman lidar including balloonborne sensors such as frost point hygrometers, as used in this study, Lyman-Alpha instruments [Všmelet. al., 2007c], and satellite measurements such as MLS [Všmel et. al., 2007b]. There are a few points to note in considering the measurement of lower stratospheric water vapor with a Raman lidar. First, as one probes higher and higher toward the tropopause with a Raman lidar located at the surface the signal is typically decreasing exponentially and the round-trip atmospheric transmission is likewise decreasing exponentially. Considering a range of 15 km from a surface location of Table Mountain at 2.3 km and a nearly

Rayleigh atmosphere, the round trip transmission at the Raman water vapor wavelength of 407.5 nm is approximately 0.45. For any range beyond 15 km, the decrease in round-trip transmission is less than an additional 10%. Second, above the cold point in the vicinity of the tropopause, the water vapor concentration assumes a nearly constant or slightly increasing value with range as opposed to the rapid exponential decrease that typically occurs in the troposphere. The combination of these two effects creates, in a certain sense, a "water vapor hurdle" for Raman lidar measurements. If the Raman lidar system can be optimized to measure to ranges of approximately 15 km, then further small increases in performance can result in large improvements in effective measurement range because the "water vapor hurdle" will have been crossed.

The typical approach to improving the performance of a Raman lidar measurement of water vapor mixing ratio is to increase the "power-aperture product" by using a larger telescope or a more powerful laser. One must recall, however, that the measurement challenge under most scenarios involves maximizing the signal-to-noise ratio (S/N) in the region of interest. That is certainly the case for Raman lidar measurements of UT/LS water vapor mixing ratio. The 0.9 value determined for the free efficiency parameter from the ALVICE water vapor channel simulations indicates that significant improvements to water vapor mixing ratio S/N might more easily come through consideration of how to reduce the noise term than how to increase the signal term as we will now attempt to clarify.

The hardware parameters that are changed to increase the signal of a lidar system include the laser power, telescope area, optical efficiency, etc. The parameters that are changed to decrease the noise of the lidar measurement are those that limit either background signal due to skylight (telescope field of view, interference filter width) or noise signal due to detector dark count rate (selection of a different detector or cooling the detector). The night of October 14, 2007 at Table Mountain, CA presented new moon conditions during the measurements. Thus the amount of skylight was approximately at the minimum expected for this mountain top location. Nonetheless, the total background count rate found on this night was comprised of approximately 18 Hz from the photomultiplier detector and 9 Hz from the sky itself. These values are to be compared with the mean signal count rate between 20 -30 km on Oct. 10 shown in figure 1 of approximately 6 Hz. Increases in S/N at this altitude would be achieved, for example, through use of a PMT with lower dark count rate. As an example of increasing the S/N through focus on the noise term, consider that the ALVICE water vapor channel S/N at the 20-30 km level could be increased by a factor of approximately $2(6/14 \rightarrow 6/27)$ if the dark count rate could be reduced from 18 to 5 Hz. Such a decrease in PMT dark count rate is achievable with a careful selection of currently available PMTs. By contrast, to achieve a factor of 2 increase in S/N through increasing the power-aperture product would be an exceedingly expensive and cumbersome task.

As an alternate way to look at the optimization challenge, consider a lidar system with

the same power-aperture specifications as ALVICE ($17.5\text{ W} \times 0.5\text{ m} = 8.75\text{ W-m}$) but with a larger field of view (1.0 mrad versus the 0.25 mrad of ALVICE) and a wider water vapor interference filter (0.5 nm versus 0.25 nm). The increased field of view and interference filter width imply that under the same measurement conditions as found on October 14, 2007 at Table Mountain the skylight + detector noise background would increase from approximately 26 Hz to 276 Hz (18 Hz using the same ALVICE detector + 32×9 for the increase in skylight). The corresponding degradation in S/N at the 20-30 km level would be from 6/27 to 6/306 or more than an order of magnitude.

The goal of NDACC is to monitor anticipated water vapor trends over the coming decades. The foregoing discussion can lead to the question of what minimum hardware configuration is needed to accomplish this task. Recent work [Boers and Meijgaard, 2009] [Oman et al., 2008] [Soden et al., 2005] indicates that during the current century maximum increases in water vapor mixing ratio can be anticipated to occur in the upper troposphere between 200 - 300 hPa (approximately 9-12 km altitude at TMF), with as much as a doubling of water vapor concentration to be expected in the lower latitude regions. In the lower stratosphere, by contrast, modeling has indicated increases of up to 20-40% [Eyring and coauthors, 2007] [Oman et al., 2008] during the same time period. The Raman lidar model used to generate figure 2 indicates that a Raman lidar system with 0.4 m telescope, 180 mJ laser operating at 10 Hz, 0.25 mrad field of view and 0.25 nm water vapor interference filter, located at Table Mountain California, would be able

to measure with 10% uncertainty to altitudes in excess of 10 km in a 2-hr period. Such a modest system could contribute to monitoring the changes in water vapor in the regions of the atmosphere where the maximum changes are anticipated and do so for a modest hardware investment. The major effort involved in monitoring water vapor trends with Raman lidar, therefore, might not be in developing hardware that has sufficient sensitivity to make the measurements at altitudes where they are needed but rather in maintaining a calibration with sufficient stability over time [Leblanc and McDermid, 2009] to create a quality dataset.

In summary, numerical simulation has been used to validate the ability of the ALVICE Raman lidar system to probe lower stratospheric water vapor. Comparisons of measurements by ALVICE and the Cryogenic Frostpoint Hygrometer on the night of October 14, 2007 showed very good agreement extending into the lower stratosphere. However, if the goal is to develop Raman lidar systems that can provide quality measurements up to the upper troposphere where the maximum increases in water vapor are expected to occur, quite modest systems that take advantage of the optimization concepts presented here can suffice.

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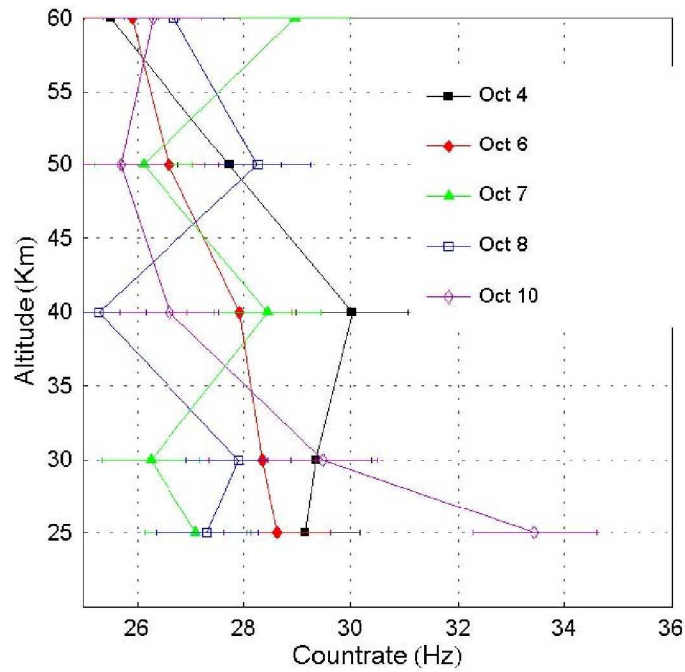


Figure 1: Watervapor channel countrates measured with long term averages on the nights of Oct 4, 6, 7, 8, 10. See text for description.

8 Figures

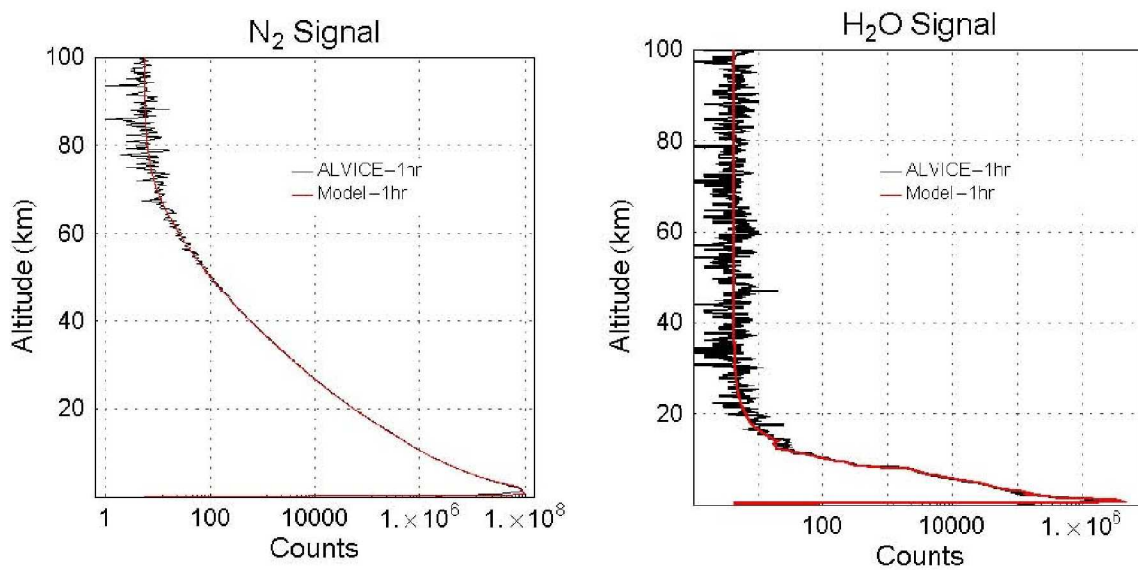


Figure 2: Comparison of ALVICE nitrogen and watervapor measurements with a numerical simulation of the performance of ALVICE for the night of October 14. The model simulations were performed

without random noises so that they can be distinguished more easily from the ALVICE data.

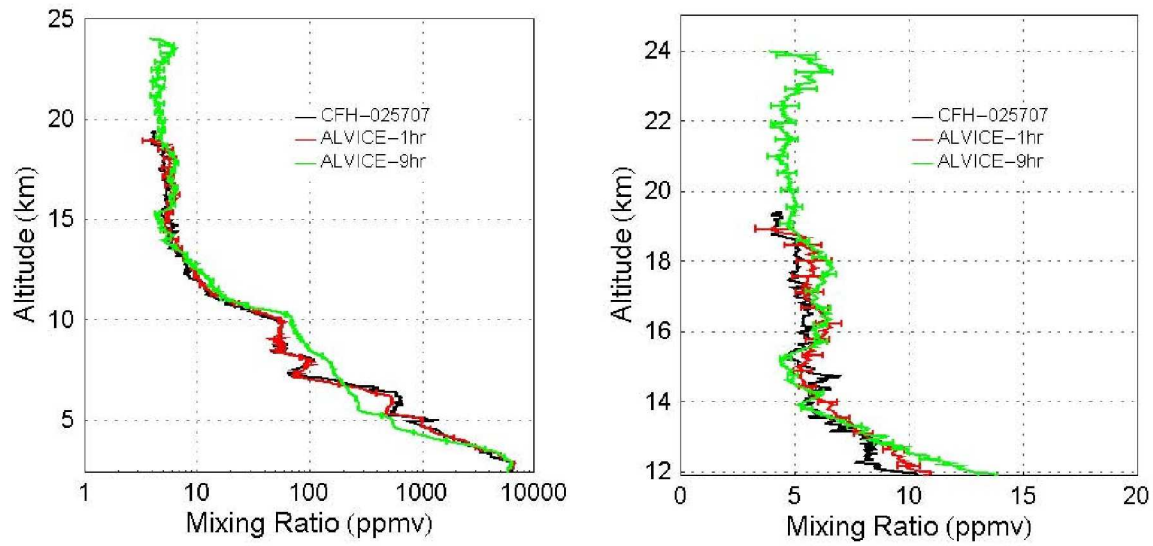


Figure 3: Comparison of water vapor mixing ratio measurements made by ALVICE and the CFH on the night of October 14, 2007. Both 1 hr and 9 hr summations of ALVICE data are shown. The error bars indicate random error assuming Poisson statistics. The plot on the right shows an expanded view of the data above 12 km.