David N.Whiteman, NASA/GSFC
Greenbelt, MD 20771,
david.n.whiteman@nasa.gov

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Airborne and Ground-based Measurements Using a High-Performance Raman Lidar. PartII: 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 andGround-basedMeasurementsUsing a High-PerformanceRamanLidar. PartII:Ground-based

DavidN.Whiteman,NASA/GSFC,Greenbelt,MD20771,

david.n.whiteman@nasa.gov

MartinCadirola,Ecotronics,LLC,Clarksburg,MD20871

DemetriusVenable andRasheenConnell,HowardUniversity,Washington,DC

KurtRush,NASA/GSFC,Greenbelt,MD20771

ThierryLeblanc andStuartMcDermid,JetPropulsionLaboratory,CaliforniaInstitute ofTechnology,TableMountainFacility,TableMountain,CA92397

HolgerVšmel,LindenbergObservatory,Germany

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 wasinstalledin a mobile trailerforground-based useduring 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 tolower stratospheric water vapor. Comparisons withCryogenicFrostpoint Hygrometer, which were launched on balloons during the campaign for in-situ validation of the lidar measurements, agreed within +/-10%. Numerical simulations were used both to 1) verify that a Raman lidar system with the configuration of ALVICE couldbe expected to operate usefullyinto thelower stratosphere and2)determine that theRaman nitrogen signal strength was reducedby approximately afactor of10during 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

TheNetworkfortheDetection ofAtmosphericCompositionChange(NDACC) has recently established long term monitoring of water vapor using Raman lidar as one of its core objectives[Leblanc andMcDermid,2009]. Some ofthe major activities undertakento addressthis objectivehave occurred attheTableMountainFacility(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 havebeen calledMeasurements ofHumidityAndValidationExperiments(MOHAVE)

[Leblanc andMcDermid,2009]. Aground-basedversion oftheRamanAirborneSpectroscopicLidar(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 earlyOctober,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 experimentsinvolved spectrally adjusting(by mechanically tilting) the central wavelength of theRamanN2 filter to maximize signal throughput,installing a reflectiveblockerinthe 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 willbebrieflydescribed.

3.1.1 Optimizing theRamanN2 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 aNASAAdvancedComponentTechnology(ACT) research effortinvolving BarrAssociates and ourRamanlidargroup[Whitemanet. al,2007]. One oftheinterference 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 whenexcitedby atripledNd:YAGlaser(~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 RamanN2 q-branch, when excitedat354.7 nm,itself covers approximately0.07-0.08 nm [Bendstenet.al.,2000]sotheuseof a filternarrowerthan0.1 nmcouldlead toasignificant reductioninsignal throughput.Becausethewidth ofthe filterusedhereisonly ~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 measurementsdescribedinpartIdue to ahost ofhigherpriorityitems that were being addressed in those first-flight efforts. The MOHAVE campaign provided good operating conditionsforperformingthistuningthrough repeatedtilting ofthe filterand 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 determinedby minimizing the changein received signal strength as afunction of changein laser output wavelength. The signal strength achieved in the Raman N2 channel after these optimizations was compared withthe signal strength achievedduringthe airborne campaigndescribedinpartI confirming thatthe0.1 nm filterwasmistunedby 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 campaigndescribedinpartI.

3.1.2 Use of a reflectiveblocker

Two ofthelidar systems usedinthe firstMOHAVEcampaignin2006[Leblanc andMcDermid,2009] used opticalfiberstorelaythesignalfromtheprimefocusofthetelescopetoareceiver box that performed the wavelength selection and detection. Fluorescence in these optical fibers was found to contaminate the upper tropospheric water vapor signal even whenusing

"High-OH" fibersaspreviously recommended[Sherlock et.al.,1999]. In

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 weakRaman water vapor signalinthe uppertroposphere andlower stratosphere(UT/LS).(Itisinteresting that oneof thevendorsevenstated "I will stakemy careeronit:thisfiberwill 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 fluorescenceinducing 355 nmlight that was transmittedinto the Raman section of the ALVICE receiver module. Long duration measurements were made under clear sky conditions to testif the addition of thisblocker made a noticeabledifferencein thefarfield ALVICE Raman water vapor signal. The results of the tests are shown in figure 1.

The figureshowsthemeanwatervaporsignalcountrate(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 ±5km from the altitude of the point shown.Forexample,thevalueshownat25kmisanaverageovertherangeof20 -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 nightis asfollows:

Date	Blocker installed?	Beam Expander Optimized?
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. TheOct. 10 measurements are addressed next.

3.1.3 BeamExpanderFocusing

Prior to operations on the night of October 10, the x5 laser beam expanding telescope was carefully adjustedfor maximize signalin thefar-field. A significantincreasein the ALVICEfar-field water vaporperformancewasachievedby thisadjustment as canbe seenin figure1.Takingthebackground countratetobeapproximately27Hz,the figure shows that the mean signal from water vapor has been increased by approximately 5 Hz at the20-30kmlevel andis now clearlydiscerned asbeing above thebackground.

4 NumericalSimulations

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 workhadbeendonepreviouslyin simulatingthe expected upward-lookingperformance underthe conditions oftheMOHAVE campaign. Therefore, one ofthe early effortsfollowing 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 couldbe expectedto measurelower stratospheric water vapor concentrations. Were real signalstruly expectedtobe measured at altitudesbeyond20km aglfrom alocationlike TableMountainasindicatedin figure1?

Apreviously validated numerical model[Whitemanet. al.,2001b] was used to addressthisquestion using data acquired onthe night ofOctober14. Onthis night,two CryogenicFrostpointHygrometer(CFH) systems[Všmel et. al.,2007] werelaunched 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. AllknownALVICE efficiency and configurationparameters werealsoincludedinthe 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 abest-fittotherealALVICEdata[Whitemanet. al.,2001b].Thisadjustable parameter accountsfor opticalefficiencies that are not explicitlyprovided 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 atthetime of theCFHlaunch was used. The values of thefreeparametersthat providedabest fittotheALVICEdatawere0.3 and0.9forthenitrogenand watervapor channels, respectively. These values reflect a design goal for RASL of optimizing the water vapor signalthroughputinthe system atthe expense ofthe nitrogen signal. It also indicates that thereislittle roomforimprovementin the water vapor signal throughput of the system. The results of the simulation comparison are shown in figure 2 where the model results arepresented without randomnoisesothatthey appear almosttobe an average of the realALVICEdata.

There is very good agreement between the combined analog and photon counting datafromALVICE(the "glued" data[Whitemanet.al.,2006a]) andthemodel 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 simulationindicatesthat real signalispresentintheALVICE water vapor data up to ranges of approximately 30 km. The comparison of the actual CFH and ALVICEmeasurementsfromOctober14 areshownin figure3 usingboth1hrand9hr summations ofALVICEdata. Theballoonthat carriedtheCFH aloftburst at an altitude of19km. A moving average smoothing wasimplemented onbothlidarprofiles using a window-size thatincreasedfrom30 meters at the surface to 1.2km above12 km. The 1hrALVICEprofileisdisplayed to19km while the9hr averageprofile extends to24 km. Atmospheric variability during the 9-hr measurement period degraded the comparison between the CFH and the 9-hr average ALVICEprofile. Overall, the ALVICE 1-hr profile and the CFH measurements agree very well with discrepancies remaining generallywithin +/-10% throughout the measurement range.

5 DiscussionandSummary

The task of quantifying upper tropospheric and lower stratospheric water vapor with sufficient accuracy to monitor trends in climate is a substantial challenge. Technologies thatare candidatesfor this taskin addition toRamanlidarincludingballoonborne sensors such asfrostpointhygrometers, as usedinthis study,Lyman-Alphainstruments [Všmelet. al.,2007c],and satellitemeasurementssuch asMLS[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 2.3km and a nearly

Rayleigh atmosphere, the round trip transmission at theRaman 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 havebeen crossed.

Thetypical approach toimproving theperformance of aRamanlidar 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 scenariosinvolves maximizing the signal-to-noise ratio (S/N)in the region ofinterest. Thatis certainlythe caseforRamanlidar measurements of UT/LS water vapor mixing ratio. The 0.9 value determined for the free efficiency parameterfrom theALVICEwater vapor channel simulationsindicates 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 includethelaserpower,telescopearea,optical efficiency, etc. Theparametersthat are changed todecrease the noise of thelidar measurement are those thatlimit eitherback-groundsignalduetoskylight(telescope field of view,interference filterwidth) ornoise signalduetodetectordark countrate(selection of adifferentdetector or cooling the detector). The night ofOctober14,2007 atTableMountain,CApresented newmoon conditions during the measurements. Thus the amount of skylight was approximately at the minimum expected for this mountain top location. Nonetheless, the total back-groundcount ratefound on this night was comprised of approximately18Hzfrom the photomultiplierdetector and9Hzfrom the skyitself. These values are tobe compared with the mean signal countrate 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 countrate. As an example of increasing the S/N through focus on the noise term, consider that the ALVICE water vapor channel S/N atthe20-30kmlevel couldbeincreasedby afactor of approximately2(6/14 Ö 6/27)if thedark countrate couldbe reducedfrom18 to5Hz. Such adecreaseinPMT dark countrate is achievable with a careful selection of currently available PMTs. By contrast, to achieve afactor of2increaseinS/N throughincreasing thepower-aperture productwouldbe an exceedingly expensive and cumbersome task.

As an alternate way to look at the optimization challenge, consider a lidar system with thesamepower-aperturespecificationsasALVICE(17.5W x0.5m =8.75W-m) but with alarger field of view(1.0 mrad versusthe0.25 mrad ofALVICE) and awider watervaporinterference filter(0.5 nmversus0.25 nm).Theincreasedfield of viewand interference filterwidthimplythatunderthesamemeasurement conditionsasfound on October 14, 2007 at Table Mountain the skylight + detector noise background would increasefrom approximately26Hz to276Hz(18Hz usingthe sameALVICEdetector + 32 * 9 for the increase in skylight). The corresponding degradation in S/N at the 20-30kmlevel wouldbefrom6/27 to6/306 or more than an order of magnitude.

The goal of NDACC is to monitor anticipated water vapor trends over the coming decades. Theforegoingdiscussion canleadto thequestion ofwhat minimumhardware configurationis neededto accomplishthistask. Recent work[Boers andMeijgaard,2009][Omanet. al,2008][Sodenet. al.,2005]indicatesthatduringthecurrentcentury maximum increases in water vapor mixing ratio can be anticipated to occur in the upper tropospherebetween200 -300hPa(approximately9-12kmaltitudeatTMF),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 to20-40%[Eyring and coauthors,2007][Omanet. al,2008] during the sametime 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 withRamanlidar, therefore, might notbeindeveloping 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 andMcDermid,2009] to create aqualitydataset.

In summary, numericalsimulationhasbeen usedto validatethe ability oftheALVICE Ramanlidar systemtoprobelower stratospheric water vapor. Comparisons ofmeasurements by ALVICE and the Cryogenic Frostpoint Hygrometer on the night of October 14,2007showed verygood agreement extendingintothelower stratosphere. However, ifthegoalistodevelopRamanlidar systems that canprovidequality measurements up to the upper troposphere where the maximumincreasesin water vapor are expected to occur,quite modest systemsthat take advantage of the optimization conceptspresented here can suffice.

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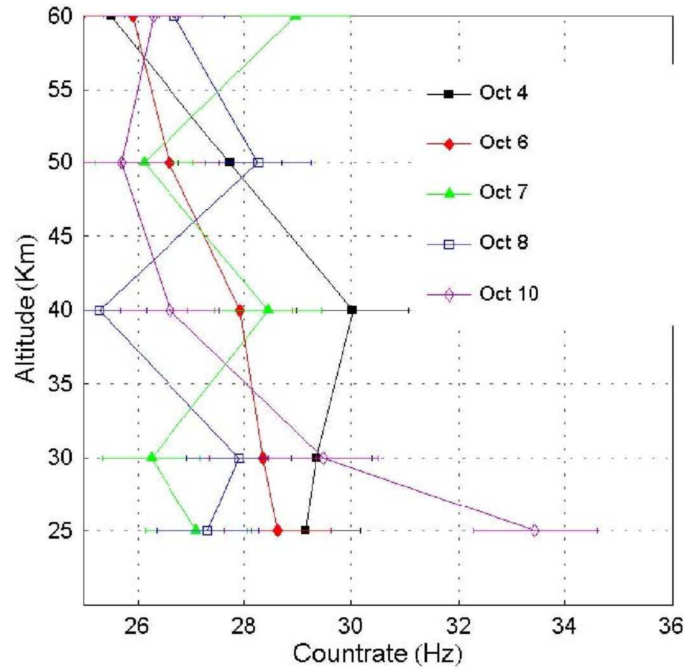

Figure 1:Watervaporchannel countratesmeasured withlong termaveragesonthe nights ofOct4,6, 7, 8,10. See textfordescription.

8 Figures

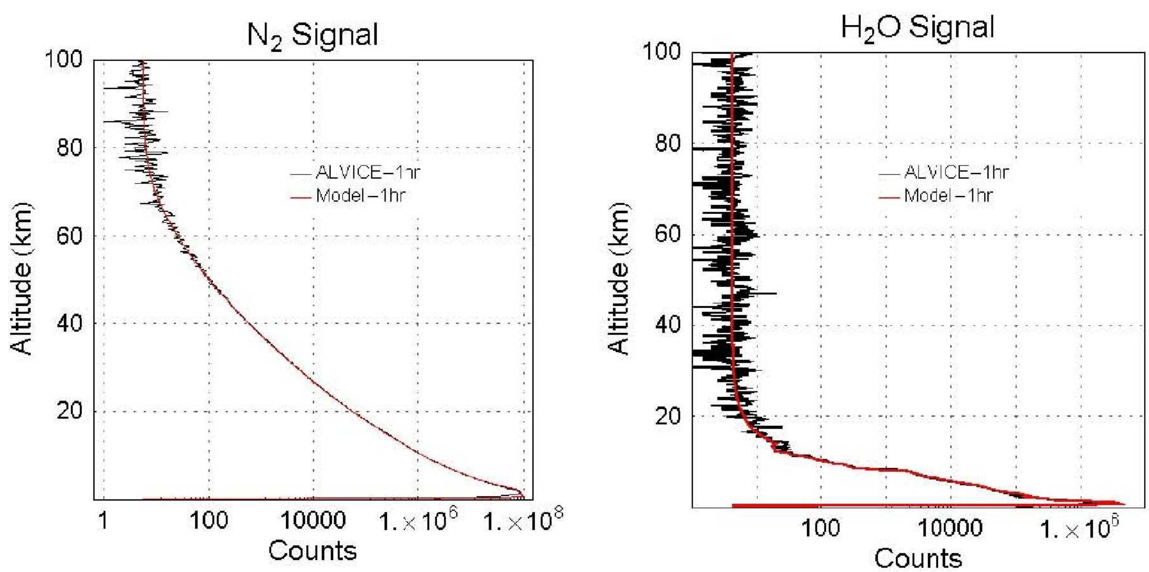

Figure2:ComparisonofALVICEnitrogenandwatervapormeasurementswitha numerical simulation of the performance of ALVICE for the night of October 14. The model simulations were performed

withoutrandom noisesothatthey canbedistinguished moreeasilyfromtheALVICEdata.

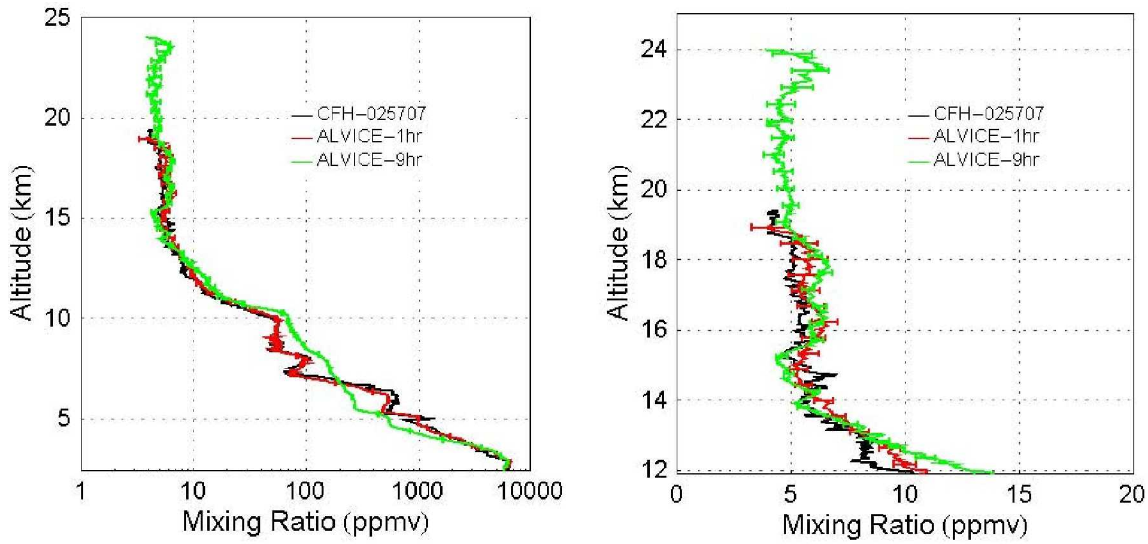

Figure 3: Comparison of water vapor mixing ratio measurements made by ALVICE and the CFH on the night of October 14, 2007. Both 1 hr and 9 hr summations or ALVICE data are shown. The error barsindicaterandomerrorassumingPoissonstatistics.Theplotontherightshowsanexpanded view
o the data above 12 km.