Simultaneous remote measurements of atmospheric temperature and humidity using a continuously tunable IR lidar

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The possibility of accurate remote measurements of temperature and humidity using a three-wavelength differential absorption technique is discussed. Selection of water vapor absorption lines for the measurement promises highest accuracy for temperature measurements and also allows the simultaneous determination of absolute humidity. Preliminary measurements of average temperature and humidity over a 775-m long path using a continuously tunable infrared lidar are reported. For the temperature measurements a relative accuracy of 1.4°C was observed. The absolute error, however, is presently ~5°C due to inaccuracies in the wavelength selection of the lidar transmitter. Humidity was measured with a 1.5% relative error limited by return signal fluctuations. The method is feasible for depth resolved measurements of temperature and humidity.

1. Introduction

Interest in remote temperature measurements has grown in recent years. Measurement of atmospheric temperature profiles with a 2-km range resolution and 1°C accuracy is required to allow better understanding of weather. Presently passive temperature sounding techniques allow profiling with a resolution of 1–2 scale heights (8–16 km) and a 2.5°C accuracy.

Several temperature probing techniques using light beams have been proposed. As early as 1953 Elterman measured stratospheric temperature profiles with a searchlight technique. Temperature was obtained from measured density variations. With searchlights, this procedure is not applicable in the troposphere due to unknown aerosol particle scattering. Laser techniques have been proposed using Raman scattering or the use of different wavelengths to determine atmospheric density fluctuations and thus derive temperature profiles. However, the calibration of the obtained temperature data must be done with an independent measurement.

Calibrated temperature measurements are possible with a technique proposed by Cooney. The rotational Raman spectrum of nitrogen allows the determination of atmospheric temperatures with good accuracy. Recent experiments demonstrated depth resolved temperature measurements to 2300-m altitude with a 1°C relative error. Although in the reported measurements the data were calibrated with measurements from a radiosonde, absolute temperature measurements are possible with this technique.

The temperature dependence of the population in molecular levels can be used to probe atmospheric temperatures with absorption measurements. For remote temperature measurements using a lidar three different wavelengths are required. Two frequencies are transmitted on the absorption lines of a species, while the third one is used for calibration of the lidar. A computer simulation of this method shows that temperature profiling from the ground or an airplane is feasible.

Only a few experiments have been reported to support the theoretical analyses. Murray et al. used a CO$_2$ lidar to measure the average temperature over a 5-km long path. However, only two frequencies were used in this measurement, and the temperature was derived under the assumption that the partial pressure of CO$_2$ in the atmosphere is constant. Correlation of the remotely measured temperature with thermometer measurements shows the feasibility of the method, although absolute errors in excess of 5°C occurred. Kalshoven et al. also reported a two-frequency measurement of temperature using a cw dye laser to probe...
oxygen absorption lines.14 A relative error of 0.5°C was observed in measurements over a 1-km long path.

We report single-ended remote temperature measurements using a three-frequency method. A theory is derived which allows the use of species with complex absorption spectra and assessment of temperature accuracy. We selected H2O as the absorbing species for our measurements. Water vapor not only promises the highest sensitivity for a remote temperature measurement, but it also allows the simultaneous measurement of absolute humidity which is of interest for meteorology.15

II. Theory

The temperature dependence of the population in molecular levels causes a variation of an absorption cross section \( \sigma(\nu,T) \) at frequency \( \nu \) with temperature \( T \). The absorption cross section is given by

\[
\sigma(\nu,T) = S(\nu,T)/\pi \gamma(T),
\]

where \( \gamma(T) \) is the halfwidth at half-maximum of the absorption line. The temperature dependence of the absorption line strength \( S \) is given by the Boltzmann distribution \( \exp(-E^0/kT) \) and a partition function \( Q(T) \) by

\[
S(\nu,T) = S(\nu,T_0) \frac{Q(T_0)}{Q(T)} \cdot \exp \left[ \frac{E^0}{k} \frac{(1 - 1/n)}{T_0/T} \right] (2)
\]

for an arbitrary reference temperature \( T_0 \), where \( E^0 \) is the lower state energy of the transition at frequency \( \nu_1 \), and \( k \) is the Boltzmann constant. The temperature dependence of \( \gamma(T) \) can be described by

\[
\gamma(T) = \gamma(T_0) \cdot (T_0/T)^n. (3)
\]

In the Doppler broadened regime, \( n \) is independent of the transition and given as \( \frac{1}{2} \). If the collision parameters are temperature independent \( n = \frac{1}{2} \) in the pressure broadened regime. In general, however, the parameter \( n \) depends on the transition. Benedict and Kaplan14 numerically calculated values of \( n \) for water vapor pressure broadened with N2. They found values ranging from 0.756 to -0.045 dependent on the linewidth of the transition.

The temperature dependence of the absorption cross section is then

\[
\sigma(\nu,T) = \sigma(\nu,T_0) \cdot \left( \frac{T_0}{T} \right)^n \cdot \frac{Q(T_0)}{Q(T)} \cdot \exp \left[ \frac{E^0}{k} \frac{(1 - 1/n)}{T_0/T} \right] (4)
\]

In atmospheric measurements the absorption cross section is not determined directly. The differential absorption measurement determines the absorbance \( A(\nu,T) = 2N \cdot R \cdot \sigma(\nu,T) \) due to the absorption line. Here \( N \) is the number density of the absorbing species, and \( R \) is the range over which the measurement is made.

The absorbance can be measured using the lidar principle. Two different measurement modes are possible:18 long path average measurements of the absorbance using topographic targets as the noncooperative backscatterer or depth resolved determination of the absorbance using Rayleigh and Mie scattering as the reflector. Vertical profiling and remote mapping of temperature are possible with the latter mode of operation. In the visible and UV, depth resolved measurements over a 1-km long path require transmitted energies of the order of 5 mJ. In the infrared, however, decreased backscattering coefficients and detector sensitivity require about 100 times that energy for the same performance. The SNR of the received signal can be improved by averaging over several laser pulses.

To remotely determine the temperature the factor \( N/R \) must be measured independently. This can be done using another absorption line of the same species. The measurement of temperature then requires the transmission of three different frequencies, \( \nu_1 \) and \( \nu_2 \) on the selected absorption lines, and \( \nu_3 \) as reference to calibrate the return signals. From the received signals \( R(\nu_i) \) at the different frequencies we determine the absorbance as \( A(\nu_i,T) = 1/N[R(\nu_i)/R(\nu_3)] \) for \( i = 1, 2 \). Then the temperature is given as

\[
T = T_0 \cdot \left[ 1 - \frac{kT_0/\Delta E^0}{1 + \Delta n kT_0/\Delta E^0} \cdot \left[ \ln \frac{A_1}{A_2} + \ln \frac{A_3}{A_2} \right] \right]^{-1}. (5)
\]

where \( A_i = A(\nu_i,T) \), \( \sigma_i = \sigma(\nu_i,T_0) \), \( \Delta E^0 = E^0_1 - E^0_2 \) is the difference in lower level energies, and \( \Delta n = n_1 - n_2 \) is the difference of the exponents describing the temperature dependence of the linewidths. In the derivation of Eq. (5) we used the linear approximation for the logarithm of \( T/T_0 \). If we further linearize Eq. (5) we obtain, for \( A_1/A_2 \ll \sigma_1/\sigma_2 \exp(\Delta E^0/kT) \) or \( T - T_0 \ll T_0 \),

\[
T = C \cdot \ln \left( \frac{A_1}{A_2} \right) + D,
\]

with

\[
C = \frac{kT_0^2}{\Delta E^0} \left( 1 + \Delta n \cdot \frac{kT_0}{\Delta E^0} \right)^{-1}, \quad D = C \cdot \ln \left( \frac{A_3}{A_2} \right) + T_0. (6)
\]

The constant \( D \) can be found either using spectroscopic data, or it can be determined empirically with calibrated temperature measurements.

It is straightforward to calculate the density of the species from the measured absorbances if the absolute size of the absorption cross sections is known. This means that the temperature measurement and the concentration of the absorbing species can be probed simultaneously.

The accuracy of a remote temperature measurement is determined by the error of each absorbance measurement. If we express the uncertainty in each measurement by the SNR of the least attenuated signal, we find the temperature uncertainty \( \Delta T \) for small \( \Delta n \) as

\[
\Delta T = \frac{kT_0^2}{\Delta E^0} \cdot \frac{1}{S/N} \cdot \left[ \frac{2}{\left( 1 + \exp(2A_1) \right)} \right]^{1/2}. (7)
\]

We see that the accuracy of the measurement is inversely proportional to the difference in lower level energies. It can also be noted that the relative error \( \Delta T/T \approx \Delta T/T_0 \) increases linearly with reference temperature \( T_0 \).

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In addition the temperature accuracy depends on the absorbance due to the probed lines. As can be seen in Fig. 1 this error factor rises rapidly for absorbances $A < 0.5$ and $A > 2$. The best temperature accuracy is achieved for $A \approx 1.1$. Then Eq. (7) simplifies to

$$\Delta T \approx 4 \frac{kT^2_0}{\Delta E^0} \frac{1}{S/N},$$

We see that it is important to select lines with enough strength to allow an appropriate absorbance over a selected path. A tunable laser source is in general necessary to select such absorption lines.

The maximum lower level energy differences in vibrational–rotational bands are typically $\sim 800$ cm$^{-1}$. For probing atmospheric temperatures where $T_0 \approx 290$ K, the proportionality constant $kT^2_0/\Delta E \approx 75^\circ$C. In the best conditions, we need a SNR of 300 for a temperature accuracy of 1$^\circ$C. An additional difficulty in the use of a rotational absorption band is the 30-cm$^{-1}$ separation of the lines with large lower level energy differences. This makes tuning between them a difficult task. Generally two laser systems must be used in this case.

Some of these difficulties can be overcome by using water vapor as the absorbing species. Since the atmospheric water vapor concentration is in the vicinity of 1%, lines with high lying lower energy levels can still lead to rather strong absorption over atmospheric paths. We can also expect to locate lines with higher lower level energy states than with other atmospheric constituents and so achieve a lower required SNR for the measurement. In addition, many vibrational–rotational bands overlap in the spectrum of water vapor which makes it possible to select lines with large lower level energy differences that are only 1 cm$^{-1}$ apart. Furthermore, the selection of water vapor allows the simultaneous measurement of temperature and absolute humidity, and so the determination of relative humidity is possible.

In addition to temperature errors due to the SNR of the received signals other noise sources are important. We will discuss those in more detail in the next section.

### III. Measurements

For our measurements we used a continuously tunable infrared lidar. Figure 2 shows a schematic of this lidar. It has been described in more detail in another paper.

An optical parametric oscillator (OPO) is used as the transmitter source. This device is unique in having a 4500-cm$^{-1}$ wide tuning range from 1.4 to 4.0 $\mu$m. An unstable resonator Nd:YAG laser is used as a pump source. The doughnut shaped output profile of the unstable resonator beam is transformed into a nearly Gaussian profile which allows more efficient and more reliable operation of the OPO. An angle phase matched LiNbO$_3$ crystal is the gain element of the OPO. Output energy is 5 mJ in a 10-nsec long pulse. The pulse repetition rate is 10 Hz.

The output beam from the OPO is collimated and expanded to a 2.5-cm diam beam and transmitted coaxially from the receiving telescope on the roof of the laboratory. This telescope is a 40-cm diam Newtonian design. It focuses the received light onto a liquid nitrogen cooled InSb detector.

A reference detector in the laboratory is used to monitor pulse-to-pulse fluctuations of the output energy. Its output signal is used by the computer to ratio the received signal and so obtain energy independent measurements.

The 5-mJ output energy of the transmitter does not allow depth resolved measurements. We used a building located 775 m from the telescope as the non-cooperative target.

We used tables of water vapor absorption lines of the 1.9-$\mu$m$^{21}$ and the 2.7-$\mu$m$^{22}$ bands in addition to the AFCRL tapes$^{16}$ for the selection of appropriate lines.

![Fig. 2. Schematic of the continuously tunable infrared lidar.](image)
For our purposes the ideal lines were found in the wings of the 1.9-μm band. We selected a J = 6 line of the ν1ν2 combination band at 5650.41 cm⁻¹ and a J = 11 line of the ν2ν3 band at 5651.33 cm⁻¹ for our measurements. These lines are within 1 cm⁻¹ of each other and so allow easy tuning of the OPO. Their lower level energies are 543 and 1999 cm⁻¹. The 1456-cm⁻¹ energy difference allows sensitive temperature measurements. In addition, the line strengths at room temperature are ~2.4 and 1.1 x 10⁻³ (atm cm⁻¹). This allows measurements over path lengths of 1 km with absorbances between 0.3 and 1.0. For these conditions we calculate from Eq. (7) that a SNR of 200 is necessary for a temperature accuracy of 1°C. If the SNR for a single return signal is 25, we expect to average over sixty-four laser pulses for the required accuracy.

We used the calculations from Benedict and Kaplan¹⁷ to obtain the exponents describing the temperature dependence of the linewidth of the selected lines according to Eq. (3). They are 0.45 and 0.30, respectively. The correction factor Δν = (κTνΔEν) in Eq. (6) is then 2%. We can neglect this correction for the constants C and D.

The first step in the measurement was the identification of the absorption lines in the laboratory and the verification of their temperature dependence. The small absorption cross sections of the selected lines made it difficult to measure absorption spectra in a short path length. Since we were not primarily interested in absolute absorption cross sections, we used a photoacoustic cell for this work. The lower traces in Fig. 3 show the signal from the photoacoustic cell filled with water vapor and air for pressure broadening at different temperatures. The upper traces show simulations of the spectrum using the spectroscopic data of the AFCRL tapes.¹⁶ Although the noise of the photoacoustic measurements is high, it can be seen that the selected absorption lines show the expected temperature dependence. Also it can be noted that the ratio of the line strengths at room temperature is different from that predicted using the spectroscopic data. This changes the calibration constant D given in Eq. (6) to a smaller value than predicted. In atmospheric measurements we used data from a recording thermograph with a ±1°C accuracy to obtain D.

For the determination of the absolute humidity from the experimental data we used the absorption cross section calculated from the AFCRL tapes for the 5650.41-cm⁻¹ line. The absolute cross-section accuracy of the AFCRL tapes limits the absolute accuracy of the humidity measurements values to 20%.

It can be noticed in Fig. 3 that the two selected absorption lines overlap. In addition more weaker lines with different lower level energies contribute to the absorbance at each of the wavelengths. For the reference transmission measurement we selected a wavelength between the two temperature sensitive lines even though at this wavelength some light is absorbed by different water vapor absorption lines. The absorption of lines with different lower energy levels causes deviations from the temperature inversion given by Eq. (5). However, we can expect to use the linear approximation given in Eq. (6) with slightly modified constants C and D.

To find these new constants we used a computer program simulating the temperature measurements. The temperature dependence of the linewidths was not considered in this simulation. Figure 4 shows the calibration curve obtained from the calculation. Here the temperature dependence of the logarithm of the calculated absorbances T* is plotted for two different linewidths of the transmitted beam.

It can be seen that the curves deviate considerably from the linear approximation given by Eq. (6) over the 100°C temperature range. However, if a maximum temperature error of 1°C is allowed, the linear approximation can be used from ~10 to 30°C. This range is wide enough to allow the use of Eq. (6) for the measurement of atmospheric temperatures in the lower troposphere.
The change in step size of the etalon drive can cause deviations at only one of the measurement wavelengths. The change in linewidth leads to small changes in the linear approximation. However, the proportionality constant $C$ changes from 36.8°C to 35.5°C or 4%. This indicates that $C$ is not strongly dependent on linewidth or line shape of the OPO.

Two effects limit the accuracy of the OPO frequency selection and thus affect the temperature measurement. The mechanical drive for the tilted etalon has a varying step size from 0.0002 to 0.03 cm$^{-1}$. This means that the wavelength of the OPO can deviate from the intended value by 0.015 cm$^{-1}$. A second limitation on the tuning accuracy is the axial mode spacing of the OPO. The mode spacing of the output at the resonated signal wave is 0.03 cm$^{-1}$. For operation with an extracavity tilted etalon only three axial modes oscillate, and small changes of the cavity length change the frequency of the strongest one. Both effects influence the accuracy of a temperature measurement.

Fig. 6. Lidar temperature measurement calibration. A total of 8.5 h of remote temperature data from different days are shown. Temperature data from a recording thermograph at the receiving telescope (solid line) were used for the calibration of lidar temperature measurements.

Drifting of the axial mode spectrum affects the wavelength of all three wavelengths for a temperature measurement in the same way. We simulated this effect and found that a frequency variation of 0.03 cm$^{-1}$ of all three wavelengths leaves the constants $C$ and $D$ effectively unchanged. Therefore, we can neglect errors from drifts of the axial mode spectrum of the OPO.

The change in step size of the etalon drive can cause deviations at only one of the measurement wavelengths.

While the variation of the reference wavelength between the absorption lines shows only small effects on $C$ and $D$, the change of any one of the two frequencies tuned on the absorption lines causes larger deviations. The proportionality constant $C$ changes 3% for a 0.03-cm$^{-1}$ variation of one of these frequencies. For measurements 20°C from $T_0$ this results in a 1°C temperature error. However, this error can be neglected compared to the change of the calibration constant $D$. A 0.03-cm$^{-1}$ variation of one frequency alone causes deviations in $D$ as large as 5.2°C. The mechanical design of the OPO transmitter allows frequency drifts of this magnitude, so deviations of the calibration constant over time scales of tens of minutes can occur.

The lower trace in Fig. 5 shows an atmospheric transmission scan with a 0.1-cm$^{-1}$ resolution tuned over a 17-cm$^{-1}$ range around the selected lines. The upper trace is a simulated transmission spectrum using AFCRL tapes. We used scans similar to this to calibrate the tuning of the OPO and to identify the temperature sensitive lines. Once the wavelength of these lines is determined and the OPO is aligned, measurements of temperature and humidity are done under computer control. The return signal at each frequency is averaged over several shots before tuning to another wavelength. To keep errors due to water vapor fluctuations small, it is desirable to tune the OPO after each shot and average the temperature data afterward. However, tuning between different wavelengths takes up to 0.5 sec. To improve the time resolution of our measurements we average 30 shots per line before tuning to the next line. When all three required wavelengths are probed, temperature and humidity are calculated. This cycle continues until a total number of 150 shots per line is reached. Then the computer calculates the average of five temperature and humidity data points, as well as the error due to return signal fluctuations, and stores and displays those values.

For calibration of our temperature measurement we minimized the difference between the remote temperature data and data from a recording thermograph at the telescope. Figure 6 shows the 8.5 h of remote tempera-
temperature data we collected during runs on three different days. The thermograph measurements are also shown. For all lidar temperature data the same calibration constant $D$ was used. The best value for $D$ was 33.9°C with a standard deviation of 2.3°C. The major factor contributing to the error margin of the calibration constant is the inaccuracy of the etalon position. Improved calibration accuracy can be expected with better frequency selection accuracy.

Figure 7 shows the record of temperature and humidity from the morning of 11 Mar. 1980. Each point represents an average of two stored data points, each using 150 shots/line. This results in a time resolution of 90 sec/point. Error bars due to fluctuations of the received signal are indicated for each point. The outside weather was cloudy at first, with rain starting at 0740. The rain increased until it was so strong at 0810 that the measurement had to be interrupted. At 0820 the rain stopped, the cloud cover slowly dissipated, and the wind increased. The remotely measured temperature is compared with a record of the thermograph at the telescope. The general agreement is good. Some discrepancies of the two measurements are expected since the remote measurement averages over a path from 10 to 60 m above the ground and 775-m length, while the thermograph is located on the roof of a building. The discontinuities of temperature and humidity measurements at 0740, 0820, and 0905 h are caused by realignment of the etalon in the OPO source. It is noticed that the drift of the transmitted frequencies can cause considerable temperature errors.

The rms deviation for each temperature measurement is calculated from the return signal fluctuations. It varies with the meteorological conditions: in the early morning, the SNR was 25. The uncertainty of the temperature measurements from 0700 to 0730 h ranges between 1.1°C and 1.6°C. This is only a factor of 3 larger than the value predicted by Eq. (6). Small changes of target reflectivity from pulse to pulse explain the increase in noise.23 The SNR decreases later due to the rain, and accordingly the rms deviations increase to values between 1.6°C and 2.0°C. After the rain stopped the SNR improved again to ~25, and the temperature uncertainty stayed between 1.5°C and 2.1°C. However, the measured values fluctuate more than indicated by the error bars because of stronger humidity fluctuations due to the wind. Any variation in absolute humidity during the 10-sec measurement cycle for each temperature point increases the uncertainty of this measurement. Shorter measurement cycles will improve the accuracy of the measurement.

Figure 8 shows a measurement taken on 21 Feb. 1980. This measurement run is interesting because a warm front moved over Stanford at 2240 h. An increase in temperature can be observed in the lidar data as well as in the thermograph data. However, the remotely measured temperature jump is larger than that measured at the telescope, as can be expected for measurements over an elevated path. Humidity data also show
an increase in water vapor concentration after passing of the warm front. It should be noted that the temperature data between 2210 and 2250 h are not reliable. A large error bar in both temperature and humidity data indicates a disturbance at 2210 h. Afterward the error bars of the temperature data are twice as large as before. Realignment of the OPO decreased the size of the temperature uncertainties to the previous levels. The continuation of the automatic measurement with the misaligned transmitter source is explained by the absence of an operator.

IV. Discussion

We have demonstrated the capability of a continuously tunable infrared lidar to measure remotely path averaged temperature and humidity. Measurements were done automatically under computer control. Selection of lines of the 1.9-μm H2O band allows good sensitivities. We achieved relative temperature uncertainties of 1.5°C for averages over 150 pulses. The relative accuracy can be improved by more rapid tuning of the transmitter to eliminate errors due to changes of the target reflectivity and water vapor fluctuations. The absolute accuracy of the measurements of 2.3°C was limited by the step size of the etalon tuning element.

The relative error of the humidity data is 1.5%. The absolute error, however, is estimated to 20% due to uncertainties in the available cross-section data of the selected lines. More spectroscopic work is necessary to improve these data.

Another noise source in the reported measurements arises from variations of the target reflectivity between laser pulses. Recent measurements show that topographic targets such as atmospheric backscattering signals have temporal correlation times of the order of a few milliseconds. The considerable improvement of relative accuracy should occur when all three probe pulses are transmitted within this time. Ways to accomplish this with a single transmitter source are under investigation.

The largest errors in the reported measurements are due to inaccuracies in the frequency selection of the OPO transmitter. Improvement of the tuning mechanism is possible and should lead to improved measurement accuracy.

Narrow linewidth operation of the OPO with an intracavity tilted etalon is possible but difficult due to the requirement for critical alignment and angle control. However, the OPO can be redesigned to avoid the need for a tilted etalon. Initial studies show that OPO operation with a 75-grooves/mm echelle grating will allow operation with a 0.15-cm⁻¹ linewidth without need for a tilted etalon.

In conclusion, we have carried out the first automatic temperature and humidity measurements using a continuously tunable lidar system. The measurements demonstrated the potential for future depth resolved temperature and humidity measurements using a higher energy tunable transmitter source. For DIAL measurements with a 150-m depth resolution at 1 km ~500 mJ must be transmitted using our present receiver/detector system. Improvements in detector sensitivity, telescope aperture, and source energy should allow remote temperature to ±1°C accuracy. Work is in progress on a significantly higher energy tunable laser transmitter that should meet the DIAL temperature and humidity transmitter requirements.

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References

1. L. Elterman, J. Geophys. Res. 58, 519 (1953).