Remote single-ended measurements of atmospheric temperature and humidity at 1.77 µm using a continuously tunable source

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Received June 9, 1980

Simultaneous remote measurements of temperature and humidity using a narrow-linewidth, continuously tunable, LiNbO₃ optical parametric oscillator as a transmitter source are reported. Relative measurement errors of 1.0°C for temperature and better than 1% for humidity over a 45-sec averaging time are observed. The absolute accuracy is limited by the accuracy of available spectroscopic data.

This Letter describes the application of our widely tunable IR air-pollution monitoring system¹ to the simultaneous measurement of atmospheric temperature and humidity. Simultaneous remote measurement of these two important meteorological parameters promises to be a useful tool for atmospheric research.

A number of groups have proposed and analyzed methods of making remote temperature measurements, and preliminary remote temperature measurements have been reported using Raman lidar² and a two-frequency absorption measurement have been reported.³ Remote temperature measurements using atmospheric-transmittance measurements of three wavelengths have been analyzed by Mason⁴ and by Schwemmer and Wilkerson.⁵ Two wavelengths ν₁ and ν₂ are selected to coincide with two absorption lines of one species with different ground-state energy Eᵢ'. A third wavelength ν₀ is tuned away from the absorption lines and is used to normalize the other two measurements. The absorbance Aᵢ is given by

\[ A_i(T) = NL \sigma_i(T) = \ln(S_{\text{off}}) - \ln(S_i), \]  

where

\[ S_i = \text{the signal received at wavelength } \nu_i, \]

\[ N = \text{the density of the species}, \]

\[ L = \text{the pathlength}, \]

\[ \sigma_i(T) = \text{the absorption cross section at } \nu_i \text{ and temperature } T. \]

The temperature dependence of the absorption cross section is given by the Boltzmann distribution and a partition function Q(T) as

\[ \sigma_i(T) = \sigma_i(T_0)Q(T)\exp\left[(E_i'/k)(1/T_0 - 1/T)\right] \]  

for an arbitrary reference temperature T₀, where Eᵢ' is the lower-state energy of the transition at νᵢ and k is the Boltzmann constant.

From the two measured values A₁(T), we can determine the temperature T as

\[ T = C T_0 + D, \]  

with \[ T = \ln A_1(T) - \ln A_2(T), C = kT_0^2/(E_1' - E_2'), \] and \[ D = C[\ln \sigma_2(T_0) - \ln \sigma_1(T_0)] + T_0(k). \]

As expected, the accuracy of the temperature measurement is inversely proportional to the difference in lower-state energies, E₁' - E₂'. Once the temperature is known, it is straightforward to calculate the density of the species.

Using selected H₂O transitions permits the simultaneous measurement of temperature and H₂O concentration and thus of relative humidity. Because of the complexity of the spectrum, we used tapes supplied by the U.S. Air Force Cambridge Research Laboratory (AFCTRL) to select H₂O lines with appropriate absorption cross-section and ground-state energy differences.

For our measurements, the optimum absorption lines were found in the 1.9-µm-band region. The J = 11 line at 5651.33 cm⁻¹, with a lower-state energy of 1999 cm⁻¹, and a nearby J = 6 line at 5650.41 cm⁻¹, with a lower-state energy, were selected since their absorption cross sections at room temperature are of similar strength and their absorbance is approximately unity at average H₂O concentrations over a 1-km path. The 1456-cm⁻¹ difference in lower-state energy yields a 0.8°C temperature error for a 1% accuracy in determining the absorbance at ν₁ and ν₂.

One problem does arise with this selection of lines. At each wavelength, not only do the selected lines contribute to the measured absorbance; the wings from some strong nearby lines and many weaker, but not negligible, lines also contribute. We used the spectroscopic data contained in AFCRL tapes⁷ in a computer program to simulate this interference. Figure 1 shows a simulation of a temperature measurement using the same three wavelengths as were used in the actual experiment. Here T [see Eq. (4)] is plotted against the actual temperature T. Overlapping of the two main absorption lines and the influence of other lines and second-order effects make T a nonlinear function of T. However, the linear approximation Eq. (4) holds to better than 10⁴ accuracy from -20 to 30°C. Variation of the spectral resolution in the computer simulation shows only small changes of the constants C and D for temperatures above -20°C. Spectroscopic data used
in this simulation have line-strength errors of about 20%, whereas the lower-state energies are known to 0.02 cm\(^{-1}\). The line-strength error affects the constant \(D\), whereas the value for the proportionality constant \(C\) is accurate. In actual measurement, we had to use a value for \(D\) that is 20°C less than that predicted in the simulation. We are working to improve the spectroscopic data by using our tunable source.

The experimental setup is an improved version of the LiNbO\(_3\) optical parametric-oscillator (OPO)-based air-pollution monitoring system.\(^1\),\(^2\) An unstable resonator–Nd:YAG laser is used to pump an angle phase-matched LiNbO\(_3\) OPO. The OPO is continuously tunable over a 4500-cm\(^{-1}\)-wide range, from 1.42 to 4.0 \(\mu\)m. It generates 10-mJ output energy in a 5-nsec-long pulse with a 10-Hz repetition rate. It has operated reliably for more than one year. Details of the tunable source have been reported earlier.\(^2\),\(^8\)

The linewidth of the OPO is narrowed to 0.7 cm\(^{-1}\) by using an intracavity grating. A tilted étalon further reduces the output linewidth to 0.1 cm\(^{-1}\). This source is continuously tunable by using a PDP11 E10 minicomputer to set crystal angle, grating, and étalon. The OPO output is expanded to a 2.5-cm-diameter beam and directed to the roof of our laboratory, where it is coaxially transmitted through the telescope. The 40-cm-diameter receiving telescope focuses the received light onto a liquid-nitrogen-cooled InSb detector.

Since the output energy of the OPO is not adequate for differential absorption measurements using Mie backscattering, we were limited to long-path absorption measurements using a building at a distance of 775 m as a backscattering target. The height above ground level of this path varies from 10 to 60 m.

A computer was used to tune the OPO and for data taking, averaging, storage, and display. An extensive interactive routine was developed to obtain atmospheric-transmission spectra and to make automatic temperature and humidity measurements. The lower trace in Fig. 2 shows an example of an atmospheric-transmission spectrum with a 0.1-cm resolution tuned over a 17-cm\(^{-1}\) range. The upper trace is a simulated transmission spectrum made by using the AFCRL tapes.\(^7\) We used scans similar to this to calibrate the tuning of the OPO and to identify the temperature-sensitive lines.

Once the wavelengths of these lines are determined and the OPO aligned, temperature and humidity measurements are made under computer control. The return signal at each frequency is averaged over several shots before we tune to another line. The time of this average has been optimized to minimize errors that are due to water-vapor fluctuations but to achieve maximum time resolution of the measurement. The OPO is now tuned after 30 shots or 3 sec, which is a good compromise in calm atmospheric conditions. After all three lines are probed, temperature and humidity are calculated, displayed, and stored. Further averaging can be done later; this reduces the storage space required. Also, the standard deviation of each quantity resulting from return-signal fluctuations is determined and stored.

Figure 3 shows the record of temperature and humidity from the morning of March 11, 1980. Each point represents 150 shots/line or averaging over 45 sec. The standard deviation was 1.1°C in the beginning but increased to 1.4°C at 0800 h. The outside weather was cloudy at first, with rain starting at 0740. The rain then 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 a thermograph at the telescope. The general agreement is good. Some discrepancies in the two measurements are expected since the remote measurement averages over a path from 10 to 60 m above the ground and 775 m in length, whereas the thermograph is located on the roof of a building.

The calibration of our data is done by using a large number of remotely measured temperature values (we have accumulated a total of 10 h of data) and comparing...
them with the thermograph data. We found that the best value for the constant $D$ is 35°C, which is 19°C less than the value predicted from the available spectroscopic data.

Our data for humidity measurement have not been checked with an independent instrument so far. We used the absorption strength for the 5650.41-cm$^{-1}$ line from the AFCRL tape, so the accuracy is estimated to be ±20%. We compared our values with relative humidity and temperature measurements at nearby meteorological observation stations. Although the trend of station data confirmed ours, the local fluctuations were too big to improve the calibration for our data.

We have demonstrated the feasibility of measuring temperature and humidity simultaneously by using a high-resolution, continuously tunable source. Absorption lines in the 1.9-μm H$_2$O band have large enough energy differences in the lower states to permit temperature measurements to be made with 1°C accuracy. Fluctuations of the H$_2$O concentration do not cause measurement problems as long as the time for each measurement is shorter than the period of these fluctuations.

Our Nd:YAG-pumped, LiNbO$_3$ OPO-based, remote monitoring system proved to be reliable. Operation at narrow linewidth was necessary to resolve the H$_2$O lines, and the use of a continuously tunable source was essential for optimum line selection. Finally, full computer control was utilized for automatic, long-term remote measurements.

In conclusion, we have measured temperature to 1°C accuracy with a time resolution of 45 sec and determined the H$_2$O concentration with a relative error of less than 1%. However, the absolute accuracy of the humidity data is limited at present by the accuracy of the available spectroscopic data.

We wish to acknowledge the support of the U.S. Army Research Office through contract #DAAG29-77-G-0181 and the Electric Power Research Institute for the continued use of equipment.

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