A Two-Path, Two-Wavelength Ultraviolet Hygrometer

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ABSTRACT

An ultraviolet-absorption hygrometer for airborne use was designed and tested. Here the principles of operation, the design, and the results of the first test flights are presented. The motivation for the new design is to overcome the shortcomings of existing Lyman-α devices. To solve the problem of source drift, a second optical path is employed as a reference. To address the problem of window contamination, a second ultraviolet wavelength is used. In addition, detector offsets are measured and subtracted from the signals. The flight data clearly demonstrate the value of both the reference detector and the second wavelength.

1. Introduction

We have designed an optical instrument for the airborne measurement of atmospheric water vapor that employs the differential absorption of two wavelengths in the vacuum ultraviolet (UV). The motivation for this design is to address the well-known problems that exist with the widely used Lyman-α hygrometers, which also operate in the vacuum UV, but at a single wavelength. Data from such devices are typically corrected by means of data from a second, slow-response hygrometer and application of a suitable algorithm (Friese et al. 1986; Schanot 1987). Various correction schemes have been developed to make the data useful, but clearly it would be preferable to eliminate this dependence on a second instrument.

Current UV hygrometers used in rapidly changing environments suffer from unexplained drifts and discontinuities in their outputs. The likely candidates for these changes are 1) inconstancy of the lamp intensity or discharge geometry, 2) drifts in the detector electronics, and 3) degradation of, or contamination on, the windows. (Such contamination might be caused, for example, by liquid water or salt deposits from sea spray.) These three factors lead to variations in output that may be difficult to distinguish from variations in humidity, and all three are addressed in the new design:

1) The lamp intensities are measured by a second detector through a nonabsorbing path that is geometrically similar to the sample path.

2) Detector drifts are measured by periodically turning the lamps off and recording the detector offsets.

3) The degradation of window transmission or detector response is measured by employing light of a second wavelength that is not strongly absorbed by water vapor. Solids or liquids in the path (or on the windows) have broadband absorption features and are essentially opaque at UV wavelengths, so absorption at both primary and secondary wavelengths should be approximately the same for closely spaced wavelengths. Similarly, changes in detector response caused by bias changes, amplifier gain changes, and like mechanisms are approximately the same for both wavelengths.

As will be explained, each measurement of humidity is derived from six measured values, rather than one, and an algorithm is employed that automatically compensates for the three types of instrumental variation, so that they are not mistaken for humidity variations. In so doing, ratios of voltages rather than absolute values are used in the analysis to allow easy calibration and reliable, low-noise measurements.

The principal wavelength is the Lyman-α line of hydrogen (H) at 121.6 nm, and the secondary reference wavelength at 123.6 nm is from the spectrum of krypton (Kr). (A secondary Kr line is discussed in the next section.) The lamps are of the electrodeless discharge type, and the detectors are standard nitric oxide (NO) ionization cells.

Ultraviolet hygrometers using Lyman-α radiation have been discussed by Tillman (1965, 1991), Buck (1985), and others. Commercial units have been available for a number of years. In an attempt to account for some of the instabilities in such instruments, Buck (1976) proposed to mechanically vary the pathlength of the hygrometer. Such an arrangement is cumbersome and suffers from reduced sensitivity when the pathlength is not optimum for the humidity range.
of interest. Campbell and Tanner (1985) used a krypton lamp with ring electrodes and DC excitation in a ground-based instrument to avoid some hydrogen lamp problems, but they conclude that sensitivity is reduced and the effects of interfering gases increased by changing from Lyman-α to krypton wavelengths. Mestayer et al. (1985) used a hydrogen lamp with DC excitation and a capillary discharge region to help stabilize the lamp output.

Zuber and Witt (1987) reported on a Lyman-α hygrometer using a reference path with separate detector in addition to the atmospheric measurement path. They also departed from most previous work in using an electrodeless lamp with radio-frequency excitation to a feeding antenna in a reentrant capillary. The reference and measurement paths use different discharge regions of the same hydrogen lamp.

A major difference from previous work in the instrument that we have developed is a second wavelength to monitor the absorption by constituents other than water vapor (such as window degradation or droplets) in the sample path. By using the two wavelengths alternately, the addition of the reference wavelength does not add to the number of detectors or amplifiers used. Our lamp reference path views the same region of the lamps as does the sample path, which eliminates the effect of discharge inhomogeneity on the water vapor measurement. We determine detector background signals to eliminate the effect of offsets. To explain more fully the use of these references and offsets, the principles of operation are next discussed in some detail.

2. Principles of operation

Figure 1 shows the optical layout of the instrument. Light from each of the two lamps (labeled H and Kr) is divided, one at a time, by an optical beam splitter so that part falls on the reference detector R and part on the signal detector S. The reference detector views the lamps through a nonabsorbing path that is geometrically similar to the sample path (it differs only in not having a lens to simplify the layout), while the signal detector views them through the sample path. For each of the lamps, an intercalibration of the two detectors is performed with a nonabsorbing gas in the sample volume. For a given lamp, this ratio of the two outputs, when combined with a real-time measurement of the reference detector output, enables one to compute the maximum possible output from the signal detector. Any smaller value is due to absorption by gases (or particles) in the sample volume or by contamination on the windows. In addition, before any of the detector outputs is used to calculate absorption, the detector zero level (lamps off) is removed by subtraction.

The ideal choice for the second wavelength would be one that is not absorbed by water vapor at all, but that suffers precisely the same absorption by window contamination as does Lyman-α radiation. Then any reduction in the output from the signal detector for this second lamp would be due to window contamination (except, possibly, for other gases). The output of the signal detector for the Lyman-α light could then be adjusted for the same fractional loss due to window contamination. In practice, any slight absorption by water vapor at the second line simply results in a decrease in sensitivity for this differential technique, and it is accommodated in a straightforward fashion, since it is the cross-section difference that appears in the analysis below.

Figure 2 (Watanabe et al. 1953) shows the spectrum of water vapor in the region of the Lyman-α line. The absorption results from electronic transitions in the molecule, so the absorption lines are much more widely spaced than are vibration–rotation transitions, which occur in the infrared. From the spectrum it is possible to assess qualitatively how flexible the choice of operating wavelengths is.

The Kr line was chosen for two reasons. First, it is close to the Lyman-α line (2.0 nm away), so it is likely to suffer the same attenuation by contaminants on the window. The closeness also allows ionization detectors to be used. Second, the absorption by water vapor of the Kr line is only 27% of that at Lyman-α. (See Table 1 for the cross sections that are used.) Thus, there is only a 27% loss in sensitivity. The principal penalty to
be paid for use of the Kr line is the greater absorption of it by oxygen, so that a much larger correction for oxygen is required than for a simple one-lamp, Lyman-$\alpha$ device. However, since pressure and temperature can be measured accurately, and since the fraction of oxygen in the dry component of air may be assumed constant, the correction for oxygen is not a problem, provided that pressure and temperature are measured near enough to the ultraviolet hygrometer and with sufficient time response.

A second potential complication arising from the use of the Kr lamp is the existence of a secondary line at 116.5 nm. However, Campbell and Tanner (1985) determined that, for their Kr lamp, this line contributes only 3% to the total lamp output. Since it is very near the nominal 115-nm cutoff for the magnesium fluoride windows, they concluded that it is greatly attenuated. The coated magnesium fluoride ($\text{MgF}_2$) beam splitter in our instrument attenuates it even more. Clearly, it would be beneficial to confirm this in future laboratory studies; for now we assume this secondary line is negligible. Its possible influence on the analysis is discussed later.

One indication of the uncertainty in literature values of absorption cross sections can be obtained by comparing Fig. 2 with Table 1. Later, we determine empirical values for the ratios of differences of absorption cross sections by comparison with independent measurements of water vapor. The effect of secondary emission lines is included in that determination.

The NO cell and associated electronics produce an output voltage that is linear in the light intensity received by the detector and is given by

$$V = \Delta V + kIe^{-r},$$

where $\Delta V$ is the offset, $I$ is the light intensity incident on the sample volume, $k$ is a constant of proportionality, and $r$ is the optical depth. The optical depth is due to H$_2$O, O$_2$, and contamination on the windows.

The effects of other gases are expected to be negligible. The optical depth may be written as

$$\tau_1(\text{air}) = n(\text{H}_2\text{O})\sigma_1(\text{H}_2\text{O})L + n(\text{O}_2)\sigma_1(\text{O}_2)L + b_1.$$  \hspace{1cm} (2)

The subscript 1 denotes the Lyman-$\alpha$ wavelength, $n(A)$ is the concentration for species $A$, $\sigma(A)$ is its absorption cross section at $\lambda_1 = 121.6$ nm, $L$ is the pathlength for the light through the sample volume, and $b_1$ is the extinction due to the contamination on the window. The measured optical depth is derived from eight voltages

$$\tau_1(\text{air}) = \ln \left( \frac{(V_{R_0} - V_{R_0}')(V_{S_0} - V_{S_0}')}{{V_{R_0} - V_{R_0}'}(V_{S_1}(\text{air}) - V_{S_0})} \right).$$  \hspace{1cm} (3)

where the subscript $R$ denotes reference detector, $S$ denotes signal detector, 0 denotes offset (both lamps off), 1 denotes hydrogen lamp, 2 denotes krypton lamp, the primes denote calibration values measured with nitrogen in the sample volume, and the argument "air" indicates the one voltage sensitive to humid air in the sample volume. The argument of the logarithm function is simply the inverse of the ratio of light that could reach the S detector (in the absence of moisture) to the light that actually does reach the S detector (assuming no window contamination), with the factor involving reference voltages providing the correction for changes in lamp intensity from the time of calibration. Solving (2) for $n(\text{H}_2\text{O})$ yields

$$n(\text{H}_2\text{O}) = \frac{1}{\sigma_1(\text{H}_2\text{O})L} \left[ \tau_1 - n(\text{O}_2)\sigma_1(\text{O}_2)L - b_1 \right].$$

(4)

It is desirable to eliminate $n(\text{O}_2)$ in favor of the pressure $P$ and temperature $T$, which can be measured. The oxygen concentration may be expressed in terms of $f^v(\text{O}_2)$, its fraction by volume (or mole fraction) in dry air, as

$$n(\text{O}_2) = f^v(\text{O}_2)n(\text{dry}),$$

(5)

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Wavelength (nm)</th>
<th>Cross section $(\text{m}^2)$</th>
<th>Uncertainty (%)</th>
<th>Source*</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>121.6</td>
<td>$1.59 \times 10^{-21}$</td>
<td>6</td>
<td>K</td>
</tr>
<tr>
<td></td>
<td>123.6</td>
<td>$4.22 \times 10^{-22}$</td>
<td>15**</td>
<td>C-T</td>
</tr>
<tr>
<td>O$_2$</td>
<td>121.6</td>
<td>$1.13 \times 10^{-24}$</td>
<td>10</td>
<td>K</td>
</tr>
<tr>
<td></td>
<td>123.6</td>
<td>$3.79 \times 10^{-23}$</td>
<td>15**</td>
<td>C-T</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>121.6</td>
<td>$7.1 \times 10^{-24}$</td>
<td>20**</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>123.6</td>
<td>$1.3 \times 10^{-23}$</td>
<td>20**</td>
<td>N</td>
</tr>
<tr>
<td>O$_3$</td>
<td>121.6</td>
<td>$2.4 \times 10^{-21}$</td>
<td>25**</td>
<td>G, W</td>
</tr>
<tr>
<td></td>
<td>123.6</td>
<td>$1.2 \times 10^{-21}$</td>
<td>30**</td>
<td>G, W</td>
</tr>
</tbody>
</table>

* Sources: K. Kley (1984); C-T, Campbell and Tanner (1985); N, Nicolet (1978); G, Gal'tsev (1973); W, Watanabe et al. (1953).
** Estimated.
where \( n(\text{dry}) \) is the number density of air molecules other than \( \text{H}_2\text{O} \).

Defining

\[
x = \frac{f^\circ(\text{O}_2)\sigma_1(\text{O}_2)}{\sigma_1(\text{H}_2\text{O})}
\tag{6}
\]

and using the ideal-gas law results in the expression

\[
n(\text{H}_2\text{O}) = \frac{1}{\sigma_1(\text{H}_2\text{O})} \frac{1}{L} \frac{1}{1 - x} \frac{\tau_1}{P} \frac{x}{1 - x \ k_B T} \frac{1}{\sigma_1(\text{H}_2\text{O})} \frac{1}{L} \frac{1}{1 - x},
\tag{7}
\]

where \( k_B \) is the Boltzmann constant. When only the H lamp is used, and with modulation, the humidity may be obtained from (7) if the \( b_1 \) term is neglected. If the offsets are known or assumed to be zero, then the modulation is unnecessary. Such an instrument, however, is subject to the unknown effects of window contamination \( b_1 \).

As just described, the effects of window contamination may be removed by transmitting light of a second wavelength that is equally sensitive to the window contamination but does not get absorbed to a great extent by water vapor. All of the previous analysis may be repeated for this second wavelength from the spectrum of K\(_2\), \( \lambda_2 = 123.6 \text{ nm} \), giving, in analogy with (2) and (3),

\[
\tau_2 = n(\text{H}_2\text{O})\sigma_2(\text{H}_2\text{O})L + n(\text{O}_2)\sigma_2(\text{O}_2)\frac{1}{L} + b_2
\tag{8}
\]

and

\[
\tau_2 = \ln \left\{ \frac{(V_{R_1} - V_{R_0})(V_{S_2} - V_{S_0})}{(V_{R_2} - V_{R_0})(V_{S_1(\text{air})} - V_{S_0})} \right\}.
\tag{9}
\]

The subscript 2 applies when the K\(_2\) lamp is on.

The measurements for the two wavelengths may be combined in two ways, depending on the nature of the window contamination. The simpler (and probably more realistic) approach is to assume complete blockage of both wavelengths at certain spots on the window, so that \( b_1 = b_2 \). A second approach is to assume the presence of a contaminant that is not optically deep and for which the ratio of absorption coefficients at the two wavelengths is known. For this case the ratio of \( b_1 \) to \( b_2 \) is constant, and the magnitude of each scale with the amount of contamination present. Since most substances are strongly absorbing in the neighborhood of the Lyman-\( \alpha \) line, only very small thicknesses are required to produce essentially complete blockage, so the assumption of \( b_1 = b_2 \) will be used. When the measurements at the two wavelengths are so combined, the result from (2) and (8) is

\[
n(\text{H}_2\text{O}) = \frac{1}{\Delta\sigma(\text{H}_2\text{O})} \times \left[ (\tau_1 - \tau_2) - n(\text{O}_2)\Delta\sigma(\text{O}_2)\frac{1}{L} \right],
\tag{10}
\]

where

\[
\Delta\sigma(A) = \sigma_1(A) - \sigma_2(A).
\tag{11}
\]

For this measurement of differential absorption, the cross-section differences are what count.

Elimination of \( n(\text{O}_2) \) results in

\[
n(\text{H}_2\text{O}) = \frac{1}{\Delta\sigma(\text{H}_2\text{O})} \frac{1}{L} \frac{1}{1 - y} \left( \tau_1 - \tau_2 \right)
\times \frac{y}{1 - y \ k_B T},
\tag{12}
\]

where

\[
y = f^\circ(\text{O}_2) \frac{\Delta\sigma(\text{O}_2)}{\Delta\sigma(\text{H}_2\text{O})}.
\tag{13}
\]

The effect of 116.5-nm Kr line (as well as H lines in addition to 121.6 nm) is to modify the factors for differences of cross sections in (13). As discussed earlier, there are enough uncertainties in cross sections at the primary wavelengths of 121.6 and 123.6 nm that the effect of additional weak lines does not dominate the overall uncertainty of the measurement. Empirical values for the \( y \) factor are determined by comparison with dipowment measurements. Tillman (1991) shows that the absorption coefficient of \( \text{O}_2 \) at 116.5 nm is less than it is at 123.6 nm, and that the absorption coefficient for \( \text{H}_2\text{O} \) is also less at 116.5 nm than it is at 123.6 nm.

From (3) and (9), we obtain

\[
\tau_1 - \tau_2 = \ln \left\{ \frac{(V_{R_1} - V_{R_0})(V_{S_2}(\text{air}) - V_{S_2})}{(V_{R_2} - V_{R_0})(V_{S_1(\text{air})} - V_{S_2})} \times \frac{(V_{R_1} - V_{R_0})(V_{S_2} - V_{S_0})}{(V_{R_2} - V_{R_0})(V_{S_1(\text{air})} - V_{S_0})} \right\}.
\tag{14}
\]

The optical depth difference \( \tau_1 - \tau_2 \) is derived from six voltage measurements at the time of the humidity measurement and six more at the time of the calibration [(3) and (9)]. Each group of six is comprised of three measurements from each detector: one with only the hydrogen lamp on, one with only the krypton lamp on, and one with neither lamp on.

Up to this point, the analysis has dealt solely with the air in the sample volume. Of course, what is desired is the water vapor concentration in the ambient air, and in the event that the air has been compressed or expanded in the process of sampling, this change needs to be taken into account. The fraction, by volume, of water molecules is the same for the sampled air as for the ambient air, so the concentration in ambient air is derived from

\[
n_a(\text{H}_2\text{O}) = \frac{P_a \ T_a}{P \ T} \ n(\text{H}_2\text{O}),
\tag{15}
\]

where the subscript \( a \) denotes ambient, and as before, the quantities without subscripts refer to the sampled
air. Using (12) and (15), the water vapor concentration in the ambient air is

\[ n_a(H_2O) = \frac{P_a/T_a}{P/T} \frac{1}{\Delta \sigma(H_2O)} \frac{1}{1 - y} (\tau_1 - \tau_2) \]

\[-\frac{y}{1 - y} \frac{P_a}{k_BT_a}. \tag{16} \]

Assuming the air undergoes an adiabatic change, we can write

\[ \frac{P_a/T_a}{P/T} = \left( \frac{P_a}{P} \right)^{1/\gamma}, \tag{17} \]

where \( 1/\gamma = 0.71 \) for dry air. Thus, the ratio \( P/T \) changes by a lesser factor than does the pressure. [Note that this represents an improvement (a decrease) in the sensitivity to pressure changes in the sample volume compared to a humidity measurement that is essentially one of dewpoint, for in that case the vapor pressure is the most immediate result, and it needs to be scaled by the ratio of the pressures to the first power.] This substitution yields for the final working equation:

\[ n_a(H_2O) = \left( \frac{P_a}{P} \right)^{1/\gamma} \frac{1}{\Delta \sigma(H_2O)} \frac{1}{1 - y} (\tau_1 - \tau_2) \]

\[-\frac{y}{1 - y} \frac{P_a}{k_BT_a}. \tag{18} \]

Thus, the calculation of the ambient water vapor concentration in principle requires measurements of the pressure in the sample volume, \( P \), and the ambient pressure and temperature, \( P_a \) and \( T_a \). If \( P \) is known to be close enough to \( P_a \), then \( P \) need not be measured and the ratio of the two may be set to unity. At present \( P \) is not measured; in the future it will be, especially since rarefaction of the sampled air is consistent with the data presented later (section 5a).

A couple of things in (18) bear comment. First, the pressure dependence in (18) is noteworthy. The sensitivity to sample-volume pressure appears only in the first term; only ambient conditions appear in the second term. Also of interest is the fact that the first term is zero when the two optical depths are equal (as can well occur), and that when this occurs the humidity measurement has the appearance of coming from the second term. Since the second term contains no absorption information and may be viewed as basically the correction for oxygen, this may seem counterintuitive. To resolve this, it is useful to consider that, in its measurement of the difference in optical depths at two wavelengths, the optical signal from this instrument may be regarded as a measure of the deviation from a base state that is obtained from the ambient variables. The base state exists when the two optical depths are equal, and when this occurs the ambient water vapor concentration is simply inferred from the ambient pressure and temperature. [When \( \tau_1 = \tau_2 \) the first term in (18) is zero, and the water vapor concentration is obtained using the ambient quantities in the second term.] Even though the air in the sample volume may be compressed, what the optical measurement implies is that the water vapor and oxygen concentrations are such that the two optical depths are equal, and this is the case regardless of what the pressure change is; it depends only on the relative amounts of the two. In this special case, then, it is the ambient pressure and temperature that matter in the determination of the ambient water vapor—since they determine the ambient concentrations—and not the pressure and temperature in the sample volume.

On the other hand, for the usual case where there is a deviation from the base state, that is, where the optical depth difference is not zero, the pressure change does matter, because it determines the amount of optical depth difference that occurs for a given proportion of water vapor and oxygen. For a given proportion, the more of both, the greater the difference. As a result, the pressure ratio appears in the first term to account for the pressure change for the ambient air entering the sample volume. Because of the fact that the pressure in the sample volume enters into only the term that gives the deviation from the base state (and even there its effect is reduced by the exponentsiation), this instrument is somewhat desensitized to the pressurization that may occur in the process of sampling. This is especially true near the base state, at which there is no effect. For the wavelength pair 121.6 and 123.6 nm, the base state occurs for dewpoints in the range from \(+1^\circ\) to \(-8^\circ\), for pressures in the range from 1000 to 500 mb. Thus, this insensitivity to pressure changes is of special value for measurements in the lower troposphere. The effect of pressurization increases with the deviation from the base state.

3. Hardware

The optics and the source and detector electronics are mounted in a streamlined housing exposed to the airstream. Figure 1 shows a cross section in a plane containing the airflow. There is a channel of uniform cross section through the housing, along a chord, to allow the passage of air for sampling. This channel is also shown in Fig. 3, which gives a cross section showing the airfoil section. A view looking at the instrument along the direction of the airflow is given in Fig. 4. The fairing is designed for mounting on a plate in one of the overhead fuselage apertures or on the nose ring of the National Center for Atmospheric Research (NCAR) King Air. For the data presented here, it was mounted in one of the apertures.

The sensing head is powered and controlled by a 3.5" X 19" rack-mounted chassis containing a microcomputer. Analog signals from the detectors are digitized in the control chassis. The processor computes the argument of the logarithm function in (14) and
sends this reduced data to the aircraft data system. In addition, for the purpose of prototype testing, all of the digitized voltages are recorded on a high-density tape attached directly to the hygrometer computer. The microcomputer also controls the firing of the lamps and the temperature of the hydride arm of the H lamp.

Optical components are shown in Fig. 1. The reference detector R, the collimating lens, and the two lamps (H and Kr) are mounted in four sides of a sealed cube, filled with N₂, so that the reference detector views the two lamps through a nonabsorbing gas. The MgF₂ beam splitter (33% reflecting, 33% transmitting, and 33% absorbing, independent of polarization) is situated inside the cube at a 45° angle. The focal length of the lens is chosen so that its focal point lies within the discharge volumes of the lamps. This provides an approximately collimated beam across the sample volume. The signal detector S is mounted with its window flush with the wall on the opposite side of the sample volume. The optical pathlength, L, across the sample volume may be changed by changing the spacers between the two segments of the fairing. At present, L is 5.6 mm for experiments in the boundary layer, but it is intended to be set to the optimum value for the expected range of water vapor concentrations for each particular application.

The sources are sealed gaseous discharge lamps excited by radio-frequency (rf) fields at 100–200 MHz. Following the suggestions of Dieke and Cunningham (1952) there are no internal electrodes as there are with high-voltage direct-current (dc) lamps. The lack of contamination from the electrodes should result in much greater lamp life. In addition, geometric stability of the discharge is greater than with a dc lamp using rod and cylinder electrodes, and rapid modulation is easily achieved. Coupling the rf energy into the simple tubular lamps is done with a coil around the lamps. This geometry simplifies lamp construction and eliminates the need for high-voltage power supplies. The H lamp is filled with 1.3 kPa (10 torr) of neon (Ne) and has an arm containing uranium (U) and uranium hydride (UH₂) at a controlled temperature so as to provide a partial pressure of hydrogen at about 1.3 Pa (0.01 torr). The Kr lamp is filled with 0.47 kPa (3.5 torr) of Kr. Both lamps are made of glass and have MgF₂ windows that are sealed to the glass with a silver-silver chloride (Ag–AgCl₂) seal. This seal is used rather than a more convenient epoxy seal because it is more robust at the elevated temperatures that can result from rf heating.

The optical detectors are NO cells. These are glass tubes filled with 2.1 kPa (16 torr) of NO. The UV light enters through MgF₂ windows that are affixed with epoxy seals. The cells have cylindrical geometry with a central, axial conductor and an outer cylindrical conductor. The outer conductor is biased to −60 V, and the conduction current through the gas resulting from photoionization is collected at the central conductor. The NO cell acts as a current source, so a current-to-voltage amplifier is connected to each cell. Because of the proximity of the sensitive detector electronics to the rf circuits, which consume 5–10 W, care was taken to confine the rf fields. The cycle of lamp firing and the details of detector sampling are described in the next section.

4. Sampling and filtering

The prototype UV hygrometer is designed to operate in any one of a number of modes. Because the instrument is under the control of a microprocessor, the implementation of, and the switching between, different modes is simply a matter of changing the software.
Thus far, two modes have been implemented. One is a two-lamp mode in which there are three states: both lamps off, H lamp on, and Kr lamp on. This set of three states is repeated once every 20 ms (50 Hz), with the 20-ms period being divided equally among the three states. The other mode employs the H lamp only. It records the initial detector offsets and then turns on the H lamp continuously. Both detectors are sampled, and a humidity value is obtained 50 times a second. Equation (7) is employed with $b_i$ set to zero. In this mode there is no correction for window contamination, but there is correction for variations in H-lamp intensity. The advantage of this mode is that it allows analog filtering of the detector outputs. One additional mode has been defined but not yet tested; it employs only the H lamp, but with modulation. This allows drifts in offsets and drifts in source strength to be accommodated, but not changes in window contamination. The use of different modes and examination of their different frequency spectra are an aid in the evaluation of the instrument.

Depending on the mode of operation of the instrument, the two detectors may each be sampled one, two, or three times per cycle of the lamp firing, or per humidity measurement. For the two-lamp mode, it is three times per cycle; for the one-lamp mode with modulation, twice; and for the one-lamp mode without modulation, once. Ideally, the two detectors would always be sampled simultaneously, but since a single analog-to-digital converter with multiple input channels is used, there is a difference of 10–50 μs separating what are regarded as simultaneous samples. This will be a problem only if the detected lamp intensity, after analog filtering, is not constant over this time interval, and, because of the filtering (see later in this section), this time difference is unlikely to be a problem.

For the purpose of illustrating the problems of sampling and filtering, consider the two-lamp mode that generates a humidity measurement 50 times a second, that is, once every 20 ms. This 20-ms period is separated into three 6.7-ms intervals: one with lamp 1 on, one with lamp 2 on, and one with both lamps off. Figure 5 shows that the detector response to a step change in current, as at the time of a lamp’s ignition or extinction, is exponential. The time constant of the amplifier feedback loop was chosen to have the output settle to within 1% of the change by the start of the second half of the 6.7-ms interval. The corresponding frequency of the -3-dB point of this circuit is 240 Hz.

Although the current amplifier provides sufficient filtering at high frequencies, additional filtering would be desirable at intermediate frequencies so that frequency components in the range from 25 to a few hundred hertz are not aliased to lower frequencies. However, there is a fundamental incompatibility in maintaining adequate response to step changes in the current and improving the filtering of high-frequency components. Step changes are an essential feature of the two-lamp instrument, as follows. Even if it proves to be unnecessary to have both lamps off for the measurement of drifts in detector offset (because the drifts are negligible), it is still necessary for a single detector to view both wavelengths, one at a time and through the same windows, so that they are subject to identical blockage. There is no good alternative to such optical multiplexing that maintains the ability to correct for changes in transmission in the sample path caused by constituents other than water vapor.

Since the current amplifier is a one-pole filter without a sharp high-frequency cutoff, the sharpness may be increased by additional digital filtering. This is accomplished by sampling each detector many times and computing an average. Averaging also increases the signal-to-noise ratio. Sampling at 20 kHz alternately between detectors (10 kHz for each detector) yields 30 samples for each during a 3-ms period. The filtering provided by this sampling and averaging is limited by the fact that the averaging period is only 3 ms. We encounter the same fundamental limit as with the analog filtering; any frequency component whose period is greater than 3 ms (frequency less than 333 Hz) will not be averaged to zero. Frequencies above the digitizing Nyquist limit of 5 kHz are not a problem because the combination of the 240-Hz analog filtering and the digital filtering attenuates frequencies above 300 Hz very strongly.

The potential problem, then, is with signal and noise components in the range from 25 to 300 Hz, since these will be aliased to frequencies less than the sampling Nyquist limit of 25 Hz. In order for there not to be significant contamination of true signals at frequencies less than 25 Hz, it is necessary that the spectrum of noise and signal decrease sufficiently rapidly with increasing frequency. Assumption of the usual $\frac{1}{f^5}$ power law leads to a quantitative estimate of the magnitude of this problem. For example, the spectral power at 10 Hz will include energy aliased from 40 Hz, but the energy of the fluctuations at 40 Hz will be
smaller than those at 10 Hz by a factor of $4^{-5/3}$, or 0.099. Thus, the error in the 10 Hz component is 9.9%.
At lower frequencies the error is less, and at higher frequencies greater. So, sampling at 50 Hz is required to get data at 10 Hz and lower that is good to 10%. If sampling were done at 100 Hz, the 90-Hz signal that is aliased to 10 Hz is only 2.6% of the 10-Hz signal, again assuming a $-5/3$-power law.

The impossibility of filtering high frequencies down to the sampling Nyquist frequency is an intrinsic problem for a hygrometer that employs modulated lamps. When operated in the one-lamp mode without modulation, analog filtering down to the Nyquist frequency could be used, and this may be a useful option for some applications. Also, if experience with the ultraviolet hygrometer shows that the changes in window contamination and detector offset occur over long enough time scales, then the second lamp may be turned on only once in a while. This, too, makes analog filtering possible since rapid switching is not employed.

5. Data

a. Calibration

Optical calibration of the hygrometer involves flowing nitrogen $N_2$ through the sample channel in the sensing head. A calibration program operates the hygrometer in the two-lamp mode to average the six detector voltages for a preset time. At the end of the measurement interval, the program prints the averaged voltages and uses them to update the values in nonvolatile memory at the researcher’s option. These calibration values are the primed variables in (14). Note that, in principle, no known water vapor sample is required and that no pressure or temperature runs are needed. We do not have enough operating experience to determine how often the optical calibration needs to be done. One calibration was sufficient for our flight program.

From these six values in memory and the six detector voltages measured in flight, the data processing system calculates the optical depth difference in (14) in real time. This difference is sent to the aircraft data system (ADS), which computes the humidity. Other parameters in (18) are physical constants (cross-section differences and mole fractions) that are entered in the memory of the ADS; $P_0$ and $T_0$ are also measured by the ADS and are available for real-time humidity calculations as well as later off-line processing.

For postflight calibration, we compare data from the UV hygrometer with data from a conventional chilled-mirror dewpoint hygrometer in Fig. 6a. Clearly, the UV hygrometer underestimates the water vapor content when (18) is used with literature values for the cross-section difference, and with the assumption that the pressure in the sample channel equals the ambient pressure, $P = P_0$. Because of the directness of the optical calibration procedure, we attribute the error in humidity measurement to a combination of these two factors that appear as a single product in (18).

The first factor is significant since what counts is the effective absorption cross-section difference of water vapor, integrated in wavelength over the entire spectral range covered by the combination of lamps and detectors, and not necessarily the literature value of absorption cross section at precisely the Lyman-$\alpha$ wavelength. Both the emission spectra of the lamps and the absorption spectrum of water vapor must be considered in evaluating an effective cross section, and since the cross section at Lyman-$\alpha$ dominates the cross-section difference, we focus on the H-lamp emissions. From Fig. 2 it is obvious that if the H lamp has emission at wavelengths other than Lyman-$\alpha$ and longer than 115 nm, then the effective absorption cross section will be less than the value at 121.6 nm. Both Buck (1977) and Zuber and Witt (1987) mention H-lamp emission in
addition to 121.6 nm. It is reasonable then to correct the cross-section difference empirically—and likely downward—to provide a calibration factor for the lamps and detectors used.

The second factor is significant since there is likely to be a rarefaction of the sample air as it flows through the restricted sample channel (D. Rogers, personal communication, 1990). Since $P$ is expected to be less than $P_o$, this leads to a multiplicative correction in the first term of (18) that is in the same direction as the correction expected for the cross-section difference.

Figure 6b shows the comparison between the UV hygrometer and the dewpoint hygrometer when the product of the effective cross-section difference and the pressure factor is corrected by a factor of 0.63. This revised constant is used for the remaining data analysis for the two-lamp mode. Since this factor is significantly different from unity, it clearly points to two areas for further research: 1) evaluation of the effective cross-section difference, and 2) measurement of the pressure in the sample channel under flight conditions. The scatter in the comparison points for the UV hygrometer is approximately the same as that for the conventional Lyman-α hygrometer that was flown at the same time (not shown). Such scatter is to be expected since the time response of the dewpoint is much slower ($\sim 1$ s).

b. The value of the second wavelength

Measurements in cloud demonstrate the value of the second, reference wavelength for an airborne hygrometer. The effect of a reference source can be seen both in scatter diagrams showing overall comparisons and in particular time series.

Since all six measured voltages in (14) were recorded for test purposes, it is possible to process two-lamp data to produce corresponding one-lamp estimates of water vapor. Figure 7a is the scatterplot showing the comparison between water vapor estimated using only the Lyman-α line [with source–drift correction, as in (3) and (7) with $b_1 = 0$] and that estimated by the dewpoint hygrometer for a dataset that included cloud penetrations. Note especially the overestimates of as much as 2 g m$^{-3}$ near dewpoint estimates of 3 g m$^{-3}$. Since the large hygrometer errors are always in the direction of too little transmission in the sample path, it is reasonable to associate such outlying points with some other obscuration in the path such as suspended cloud particles or a water film partially covering the windows.

When information from a second lamp is used to correct for absorption in the sample path that is not caused by water vapor, the scatterplot of Fig. 7b results. This is for the same time period as Fig. 7a. Note how the overestimates have been brought much closer to the best-fit line. There is still a positive bias for some of the points, though much smaller than without correction. This could occur if the beam patterns of the two lamps were not quite the same at the windows. This point also merits further study.

Time-series data for a number of passes through small clouds are shown in Fig. 8. For small clouds, such those at 1049:25 and 1056:15, the humidity variation shown by the two-lamp data is very well represented by the variation inferred from one-lamp data. In other cases, particularly around 1051 and 1058, there

![Fig. 7](image-url)

(a) Scatter diagram of data derived from only the Lyman-α lamp of the UV hygrometer compared with data from the dewpoint hygrometer for a 15-min period including passes through various cloud densities. Date from the krypton lamp is not used. Thus, this simulates the standard Lyman-α hygrometer in one respect but not another. It is subject to the deleterious effects of window blockage, but it benefits from a correction for drifts in source strength. Note the many points indicating an overestimate of humidity from the Lyman-α data. These are attributed primarily to blockage of the windows by liquid water. Also, the slope is poor as no correction is made for the effective cross-section or deviation of the pressure factor from unity. (b) Scatter diagram of data from the UV hygrometer including all six measured variables compared with data from the dewpoint hygrometer for the same time period as (a). Note both the correction of the overestimated values and the improved slope and intercept of the fitted line. The correction of overestimated values is attributed to the use of the second lamp. The better slope is attributed primarily to correction for the cross-section difference and the pressure factor.
is evidence of substantial (equivalent to more than 2 g m$^{-3}$) blockage in the sample path. Data from the particle counter verify that this blockage is associated with cloud penetrations, confirming the suppositions used to explain outliers in Fig. 7a.

Peak water vapor concentrations in the cloudy regions are very close to saturation. The average temperature and pressure for 1058:00 to 1058:10 are$-6.5^\circ$C and 602 mb. The corresponding saturation water vapor density is 3.06 g m$^{-3}$, which is the value shown by the middle trace in Fig. 8 at 1058:05 within a reading uncertainty of $\pm 0.05$ g m$^{-3}$. This case illustrates the effectiveness of the second wavelength in accurately correcting for sample or window contamination, and it provides an independent verification of the empirical calibration of the instrument. The offset between the one-lamp data (with correction for source strength) and the two-lamp data in Fig. 8 is real rather than introduced to separate the traces.

c. The value of the reference path

The necessity of a reference path is clearly illustrated in Fig. 9. It shows a gradual increase in voltage from the reference detector during the on-time of the H lamp. In comparison to the lowest trace, which includes the correction for source drift, the middle trace, which does not include a source correction, shows an incorrect additional downward trend in water vapor concentration. The mechanism may be related to a variation in lamp output with ambient temperature or simply a

Fig. 9. Time series of data from the UV hygrometer in a climb from approximately 26$^\circ$C to $-6^\circ$C. The top trace (right scale) is voltage from the Lyman-α reference detector. The middle trace (left scale) is water vapor estimated from the Lyman-α data without source correction, and the lower trace, with correction. Note the overestimate at weaker source strength, which illustrates the need for the lamp reference path.

d. Frequency spectra

A frequency spectrum for data sampled at 50 Hz in the two-lamp mode (recall Fig. 5) is shown in Fig. 10. The spectrum follows the expected $-5/3$ power law to approximately 5 Hz, after which it begins to flatten out. This behavior follows the expectations of section 4 in exhibiting aliasing of higher frequencies about the sampling Nyquist frequency of 25 Hz. Although the section on sampling establishes that filtering of the two-lamp signals below approximately 300 Hz is not possible, it should be possible to reduce the effect of aliasing by filtering out, after the fact, the higher frequencies (above 5 Hz or so) in the data sampled at 50 Hz, since the effect of aliasing is expected to be significant only there and not at lower frequencies. This was not done in this study. The spectrum shows no tendency to attenuate higher frequencies, suggesting that the flow of sample air is not so restricted that it limits the frequency change with operating time. A. Schanot (unpublished work, 1989) has observed a change in Lyman-α source strength with changing temperature using a conventional de-excited Lyman-α hygrometer in a temperature-controlled chamber. During the time period shown in Fig. 9, the ambient temperature decreased rather linearly from approximately 26$^\circ$C to $-6^\circ$C. This change may or may not have had a significant influence on the source output. In any event, direct measurement of source strength is necessary for a correct measurement of water vapor content with a UV hygrometer.
response of the instrument, even though there may be a significant deviation of the pressure ratio from unity.

To show the flexibility of the programmable operation of the UV hygrometer, the instrument was operated in a truly conventional one-lamp mode with the Lyman-α lamp turned on continuously. With this mode of operation it is possible to analog filter (prior to sampling) the signals above any desired frequency because the step changes shown in Fig. 5 do not exist. For this demonstration, the (four-pole) analog filter was set to attenuate frequencies above 10 Hz. Results are shown in Fig. 11. The spectrum of the filtered signals rolls off above 10 Hz as expected. There is no evidence of aliasing at frequencies less than 10 Hz, as there was in Fig. 10 without the analog filter.

e. Sample data

Because of its ability to correct for obstructions in the optical beam and its frequency response, the UV hygrometer is particularly well suited for studies of finescale cloud dynamics. Figure 12 is an expansion around the initial penetration into the second major cloud in Fig. 8 at approximately 1058:00. In the cloud, the hygrometer generally follows temperature changes as expected for a saturated environment. The pattern of a warm spike at 58 min 8.2 s and the preceding cool spike at 58 min 7.9 s is faithfully replicated in the water vapor measurements, for example. Additional correspondences occur at 57 min 57.5 s, 57 min 58.6 s, and 57 min 59.4 s, but the warm spikes at 57 min 56.9 s and 58 min 6.1 s do not show corresponding humidity increases.

Outside the cloud there is significant inhomogeneity. The warm region at 57 min 55.6 s is also relatively moist, but the warm parcel at 57 min 52.4 s is much drier than its surroundings. There is a cool, dry parcel at 57 min 52.0 s. Other structural details can be seen. If we use the saturation humidity from Fig. 8, 3.06 g m$^{-3}$ at $-6.5^\circ$C, the hygrometer shows supersaturation of approximately 0.1 g m$^{-3}$ at 57 min 56.5 s. Of course, verification of the accuracy of the UV hygrometer at cloud edge and other details of interpreting the results depend on much more operating experience. Sample data do show promise.
6. Future developments

Although the initial flight data demonstrate great potential for this UV hygrometer, there are some areas of concern to be addressed by future work. Most obvious are the need for measurements of the spectra of the two lamps over the wavelength range to which the detectors are sensitive, 115–135 nm, and a measurement of pressure in the sample channel. It would be valuable to account for the contribution of these factors to the overall correction factor that was determined from the calibration against the chilled-mirror device. In addition, a direct laboratory measurement of the effective cross sections of water vapor and oxygen at various pressures for the two lamps would be of benefit in understanding the UV hygrometer.

Additional research aimed at lamp performance also would be valuable. The intensity of the lamps and the ease of lighting are affected by fill pressures and, in the case of the hydrogen lamp, by the buffer gas. Thus, further experimentation with different fill pressures or buffer gases could lead to improvements in the lamps. Also, since the location and size of the discharge region within the lamp can be affected by the placement of the coil around it and by the proximity of other conductors, varying these things might also lead to better lamp performance and longer lamp life. The frequency spectra indicate that faster modulation of the lamps may be desirable for improving the high-frequency data from the hygrometer. Thus, future lamp research should be directed also at higher rates of modulation. Although their work showed only a small modulation depth, Priestly and Cartwright (1982) modulated de-excited H lamps to 10 kHz. One preliminary observation indicates a potential problem with faster modulation of the hydrogen lamp employed so far. With increasing partial pressure of hydrogen (increasing temperature of the U/UH₂ arm), longer turn-on times were noted that were not quite a problem for 50-Hz modulation but could be for 200-Hz modulation. No such problems were noted, however, for the krypton lamp. Whether or not the turn-on time for the hydrogen lamp is a function of the buffer gas or its partial pressure has yet to be determined.

Research also needs to be performed on the airflow through the sample channel. How turbulent is the airflow, and are pressure fluctuations present that significantly affect the measurement? Wind-tunnel studies, or perhaps flights of a suitably instrumented housing, could answer these questions.

The best mode in which to operate the hygrometer also is not known; it may depend on the type of flight. If the window contamination is expected to vary slowly (e.g., in clear air), then operation of the instrument in a mode that uses the krypton lamp only infrequently, but keeps the hydrogen lamp on for extended periods, would allow the possibility of analog filtering of the detector outputs to avoid aliasing. (This also assumes that the drift in detector offsets is slow, and this has indeed been observed to date.) If window contamination is expected to be highly variable (e.g., in a cloud), then greater use of the krypton lamp could be employed.

Finally, a tower-mounted variant of this airborne model could be developed. If the present housing were to be employed, the addition of a vane would be required to steer the sample channel into the wind. Alternatively, a more open, omnidirectional design could be produced using the same measurement concepts.

7. Conclusions

We have presented the design of an airborne, ultraviolet-absorption hygrometer that is aimed at overcoming the deficiencies in the commonly used Lyman-α devices. The initial test flights show great promise for this new instrument. The value of the second, reference detector is illustrated in Fig. 9, which shows that the effects of source drift are effectively removed through the use of data from the reference detector.

The value of the second wavelength, as well as the second detector, is clearly demonstrated in Fig. 8. During these passes through clouds, the windows were partially blocked by condensed water, and use of the Lyman-α wavelength by itself led to erroneously high values of humidity. Use of the second wavelength enabled the determination of what fraction of the light was actually blocked by condensed phases rather than absorbed by water vapor. In this case, the amount of blockage was equivalent to more than an additional 2 g m⁻³ of water vapor, but its effect on the corrected humidity was small.

Future laboratory work will address uncertainties in absorption cross sections, lamp spectra, lamp improvements, and airflow through the sample channel. Future field experience will dictate the optimum mode of operation (especially the degree of two-lamp operation) as a function of the type of research flight.

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