**AN OPTICAL WATER VAPOR SENSOR
FOR
UNMANNED AERIAL VEHICLES**

By

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EXECUTIVE SUMMARY

This Small Business Innovation Research Phase II project involved the development of a robust, compact, low power consumption sensor for the measurement of water vapor concentrations in the troposphere and lower stratosphere on board manned and unmanned aerial vehicles. Water vapor concentrations are measured using the optical absorption of a Zeeman-split emission line of an argon discharge lamp. By applying a magnetic field of the proper magnitude, the emission line is split into two components of opposite circular polarization : one coincident and one off-resonance with respect to a water vapor absorption line at $10,687.36 \text{ cm}^{-1}$. Differential absorption is directly measured by alternately selecting the polarization of the light which is allowed to propagate down the optical path of a multi-pass absorption cell. Laboratory investigation of this technique demonstrated that water vapor concentration measurements could be obtained over a range of over three orders of magnitude (~ 0.002 - 3.0%).

A field prototype unit, comprising purchased components costing less than \$6,000, was then developed. This prototype weighed less than 6 kg and utilized less than 40 watts of power (excluding that used for heating the air sample stream). Significant features of the field instrument include: a magnet shield assembly which limits stray magnetic fields to less than 1 gauss outside the instrument chassis; a high speed ferro-electric liquid crystal which enables measurement rates of 10 Hz or greater; and a light-weight, low cost, fiber pigtailed multipass absorption cell. This instrument was installed aboard the Department of Energy Gulfstream-1 aircraft and used to measure water vapor concentrations during the ARM Intensive Operation Period (IOP) conducted in August 1998.

Data collected during these flight tests demonstrated the ability of the field prototype instrument to obtain rapid, absolute water vapor content from aircraft platforms over an altitude range of 6 kilometers. The Aerodyne Research instrument showed excellent agreement (to within $\pm 1^\circ$ dew point) with a chilled mirror hygrometer that is routinely used to record atmospheric water vapor content on a ~ 10 second time scale. Comparison with an uncalibrated, but much faster responding Lyman- α probe, also showed excellent agreement, including simultaneous measurement of transients as short as 1 second. Observations of atmospheric water vapor distributions in clear air and in and around clouds, revealed important information about the Aerodyne instrument's response to rapid variations in water vapor concentration. Large fluctuations in water vapor content ($> \pm 3^\circ$ dew point) over a distance scale of a few kilometers during level flight in clear air were observed as well as rapid water vapor changes at or near cloud edges. These experiments demonstrated that the Aerodyne Research water vapor sensor is well suited to the measurement of tropospheric water vapor distributions.

In summary, during the Phase II SBIR project described in this report, Aerodyne Research has developed, calibrated and flight-tested a novel, fast-response optical water vapor sensor. This instrument is potentially more reliable and less expensive than previously demonstrated optical water vapor sensors based on tunable diode lasers or Lyman- α fluorescence techniques. While the current version of this instrument is suited primarily for measurements in the lower and middle troposphere (altitudes up to 25,000 feet), optimization of several components would suffice to allow for measurements near the tropopause and lower stratosphere.

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1. INTRODUCTION

1.1 Background

The need for robust, low cost, compact instrumentation for the rapid measurement of water vapor concentrations over a wide range of conditions is an issue of great concern for both the atmospheric¹⁻³ and industrial sensing communities⁴. In particular, instruments are needed by atmospheric researchers for the measurement of water vapor in the troposphere and lower stratosphere using small manned and unmanned aircraft and aerial vehicles. Although there are many other greenhouse species, some naturally occurring and some anthropogenic in origin, the most important greenhouse substance is water, both as a vapor and in its liquid and solid states as cloud particles. The amount of water vapor that can exist in the atmosphere is related exponentially to the atmospheric temperature. This fact alone leads to great variability of water vapor concentrations, in both vertical and horizontal directions. Any increase in other greenhouse gases that leads to atmospheric heating, therefore, brings with it the secondary effect of a potentially large increase in water vapor simply due to a relatively small atmospheric temperature changes. Moreover, the rich absorption spectrum of water vapor, a property of its molecular structure, covers much of the region from the near infrared to the microwave region, providing a mechanism for heat exchange that is larger and spectrally more extensive than any other gaseous atmospheric constituent. Even small amounts of water vapor in the upper troposphere provide a broad spectral emitter for radiation loss to space.

Global climate models that are used to evaluate this feedback mechanism generally describe atmospheric structure using a grid of plane parallel cells in which various dynamical and equilibrium processes occur. At the sub-cell scale, however, many physical processes can depart significantly from the plane parallel approximation. For example, processes involving clouds (particularly convective clouds) are anything but plane parallel. It has been observed that convective clouds have associated water vapor halo structures in the region surrounding the actual condensed phase which we call cloud. This water vapor structure appears to bear a relationship to the dynamics occurring in the vicinity of the cloud; indeed, the cloud development and dissipation itself is most likely related to this clear air/water vapor structure. Recently published model calculations indicate that the water vapor halos associated with convective clouds may account for a significant fraction of the 'anomalous' short wave

absorption detected in recent cloud transmission experiments⁶. Therefore, any inability to accurately model the effects of highly structured clouds and their associated water vapor structures on atmospheric processes presents an extremely severe limitation on our understanding of greenhouse forcing.

Tropospheric water vapor has been shown to be variable on spatial scales of less than 1 km and temporal scales of a few minutes.⁷ Remote sensing, while capable of resolving water column densities on an appropriate scale, cannot resolve the true 3-dimensional structure. Aircraft-based instrument systems are required to explore the structure of water vapor at the required level of detail for cloud and climate studies in the lower and upper troposphere. Requirements for such a system include: absolute calibration of concentrations, fast time response (10 Hz or better), a temperature operating range of 230-310 K, and an operating pressure range of 200-1020 hPa.

In response to these needs, we have developed a novel water vapor monitor that utilizes optical absorption of an emission line emanating from a simple gas discharge lamp in the water vapor absorption band in the near infrared (~935 nm).⁸ The advantages of the gas discharge lamp, compared to the use of alternative light sources (e.g., near-IR diode lasers)⁸⁻¹³, are the stability and reproducibility of the spectral properties of the light, which results in a relatively simple and inexpensive instrument. It also offers significant advantages in range, speed, simplicity, size and low power consumption that cannot ordinarily be achieved by other types of sensors including chilled mirror, Fourier transform infrared absorption and Lyman- α induced fluorescence hygrometers.

1.2 Program Scope

The goal of the Phase II program was to develop a fully operational Optical Water Vapor Sensor that was suitable for in-situ measurements in the troposphere and lower stratosphere. In order to achieve this goal, the following tasks were completed:

- Development of the physical structure of the instrument including the lamp, optical system, instrument chassis, etc.;

- Development of the data acquisition interface hardware and software necessary to control the instrument and collect data;
- Calibration of the sensor with known water vapor concentrations and characterization of the prototype with respect to sensitivity, drift, interferences, etc..
- Participation in field trials on board a research aircraft; and
- Analysis of the data acquired in such trials and an evaluation of the significance of the measurements with respect to atmospheric chemistry.

The bulk of this report will set forth details of the progress made towards successful implementation of these tasks and achieving the primary goal of developing a working field prototype of a water vapor concentration monitor. The second chapter of this report will provide details of the operating principles behind the chosen approach and a proof-of-principle demonstration under laboratory conditions. The third chapter will describe instrumentation changes and improvements necessary to construct a field-ready prototype. A fourth chapter describes the details of the field test, installation of the prototype on the Gulfstream-1 aircraft, and field diagnostic measurements to confirm instrument calibration and noise performance during the field exercise. The fifth chapter concerns the actual test flights performed and the data that was acquired. A comparison with other water vapor monitoring instruments on board the aircraft (chilled mirror and Lyman- α hygrometers) will be presented in some detail. The sixth chapter will present data concerning the observation of atmospheric phenomena in both clear air and in the vicinity of clouds. Possible implications of these measurements will be discussed. The seventh chapter will describe the commercialization potential for this monitor; commercialization of DOE-sponsored technology is a key objective of the SBIR program. Finally, an appendix containing the complete text of a journal article describing the instrument operating principles and capabilities that appeared in *Measurement Science and Technology* [9,1793-1796 (1998)] is attached.

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2. PRINCIPLE OF OPERATION AND LABORATORY DEMONSTRATION

2.1 Operating principles

The water vapor monitor is based on utilizing the neutral argon line at 935.4 nm wavelength (10687.43 cm^{-1})^{1,2}. This line is known to be close to, but not coincident with, a strong water vapor absorption line at 10687.36 cm^{-1} ; this line is the second strongest spectral feature in the 940 nm water vapor absorption band³. When the emission line is Zeeman split⁴ by a longitudinal magnetic field of the proper strength, it is divided into one component that is strongly absorbed by the water line, and a second component that is only weakly absorbed. Figure 2A presents a detailed simulation (calculated using molecular line parameters from the HITRAN database³) of the relevant spectral profiles of the water absorption line at an ambient pressure of one atmosphere and the split Argon emission lines in a magnetic field of 1600 Gauss. As can be seen, Zeeman splitting of the emission line produces two components, one downshifted so as to overlap the maximum of the water absorption line, and one shifted to sufficiently higher frequency so as to ensure weaker absorption.

An important feature of the Zeeman split lamp line components is that they possess circular polarizations of opposite handedness. By discriminating between these polarizations, the ratio of the differential absorption of these components to the off-resonance component, $\Delta I/I_0$, can be used to determine the column density of water vapor in an open or closed path absorption cell. This can be accomplished as shown in Figure 2B, by allowing the light to pass through a quarter wave plate, which converts the two circular polarizations (of opposite handedness) to orthogonal linear polarizations. The light then passes through a $\frac{1}{2}$ wave liquid crystal rotator and linear polarizer element, such that when the appropriate square wave drive signal is applied to the liquid crystal the output is alternately switched between the two wavelengths. This dual wavelength output is then used to interrogate the gas sample of interest, resulting in a differential absorption signal that can be used to determine water vapor concentration.

Figure 2A: Computed absorption spectrum of water vapor in the 940 nm region at a total pressure of 1.0 atm and the spectral output of the Argon emission line with and without the presence of a longitudinal magnetic field. Path length = 18 m, $B = 1600$ G, $T = 295$ K, and $[H_2O] = 1.3\%$ ($\sim 50\%$ relative humidity).

Figure 2B: Principle of operation of the water vapor monitor, illustrating the polarization selection of wavelength. Output wavelengths, λ_1 and λ_2 , emitted by the argon lamp are converted to two orthogonal linear polarizations using a $1/4$ wave plate. The two linear polarizations are then alternately rotated by 90 degrees by driving a liquid crystal element. This output is then filtered with a polarizer that allows only one polarization state to pass at time, resulting in a time-switched output that can be used to illuminate the gas sample of interest to obtain a differential absorption measurement of water vapor.

2.2 Laboratory Demonstration

In order to demonstrate this approach, the optical system shown in Figure 2C was constructed. The argon discharge lamp used in these experiments was assembled from ultrahigh vacuum components. The active plasma volume of the argon lamp is defined by a glass capillary tube (2 mm i.d., 25 mm long) which fits tightly in the bore of an insulating break (i.e., an alumina ceramic section brazed to Kovar spool pieces with 3.37 cm o.d. 400 series stainless steel knife edge flanges attached). The lamp was filled with 3 Torr of ultrahigh purity argon and operated at 200V, 4 mA using a switching power supply commonly used with He-Ne lasers. Details of the lamp, magnetic circuit, and experimental set-up used in this demonstration is described in a recent publication and appears as Appendix A at the end of this report.

The light emitted by the argon lamp is collected by a lens (chosen to efficiently image the plasma volume while rejecting the light reflected from the tube walls) and sent to the polarization selection elements. In the configuration used here, a twisted nematic liquid crystal cell driven by a 5 Hz square wave is used to provide polarization selection. In order to reject unwanted lamp emission lines outside the 940 nm band of interest, the output is also sent through a narrow band interference filter. Light is then coupled to the multi-mode fiber, passed through a fiber-optic splitter, which serves as a convenient optical tap for the reference detector, and into a multipass absorption cell. The 18 meter path length off-axis multipass absorption cell (86 passes) utilizes mirrors made of glass substrates with high reflectivity (>99.5%) dielectric coatings.^{5,6} The light output from the optical cell is coupled to a high-gain transimpedance photodetection circuit (Si detectors). Common mode noise caused by lamp intensity fluctuations is then minimized by subtracting the (scaled) reference detector signal from the sensor detector signal and sending the difference signal to a lock-in amplifier in order to recover the magnitude of the 5 Hz differential absorption signal. Measurement of water vapor concentration is achieved by normalizing the lock-in output to the DC component of the combined detector signal.

In the water vapor concentration measurements reported here, a gas flow of high water vapor content in air was manufactured using a bubbler arrangement; this stream was admixed with dry air (less than 1 ppmv water vapor content) to produce mixtures ranging from 30 to 30,000 ppmv water vapor content. The gas stream containing the water vapor was flowed at

approximately 3 standard liters per minute (slpm) through the multipass absorption cell. Pressure and temperature in the cell were measured using a capacitance manometer (1000 Torr full scale) and a chromel/alumel thermocouple respectively. In order to establish the water vapor concentration in the first cell, (i.e., calibrate the sensor) the gas flow was then sent through a second multipass absorption cell which could be interrogated by a cryogenically-cooled lead-salt tunable diode laser (TDL) system which was operating at 1933 cm^{-1} . This TDL system enabled measurement of water vapor concentrations with greater than 1 ppmv precision and 5% accuracy (limited primarily by the uncertainty in the absolute absorption strength of the observed line). The TDL system is not suitable as a low cost, light-weight method of measuring water vapor; however, it was useful for purposes of providing a water vapor calibration instrument. Details of a typical TDL absorption spectrometer are given elsewhere.^{7,8} The observed absorbance ($-\ln(1-\Delta I/I_0)$) of the water vapor sensor versus water vapor concentration at atmospheric pressure is shown in Figure 2D. Note that the absorbance versus concentration measurements are not linear above 10,000 ppmv. This deviation from Beer's Law is attributed to the 'off-resonance' reference beam (I_0) actually overlapping on the shoulder of the absorption feature of interest and the non-zero spectral width of the lamp lines. Figure 2E shows a time history of the instrument response for two different steps in water vapor concentration. The noise level in this result corresponds to 3 ppmv rms for a 10 second lock-in filter time constant, which corresponds to an equivalent noise density of $\sim 20\text{ ppmv}/\sqrt{\text{Hz}}$.

We also present data taken at one water vapor concentration (970 ppmv) over a range of pressures comparable to that found in the troposphere and lower stratosphere. Figure 2F shows that over a considerable range, ~ 0.3 -1.2 atmospheres (230- 900 Torr), the sensor acts as a mixing ratio monitor (i.e., measures the fractional water content, not the absolute number density) to within an accuracy of $\pm 10\%$. Pressure-independent behavior is typical of spectroscopically-based instruments which operate in the pressure-broadened regime (i.e., where, to first approximation, the water absorption cross section is inversely proportional to total pressure). The more complicated behavior demonstrated by this instrument at high pressure indicates that this approximation does not strictly hold. At the lowest pressures measured, the water absorption cross section becomes independent of pressure and the instrument responds directly to water vapor number density.

Figure 2C: Instrument schematic of the Aerodyne water vapor monitor.

Figure 2D: Measured absorbance as a function of water vapor mixing ratio at a total pressure of one atmosphere in air at $T=295\text{K}$.

Figure 2E: Water vapor sensor output for two different step changes in water vapor concentration. Noise level in this result corresponds to 3 ppmv rms for a 10 second lock-in time constant, which corresponds to an equivalent noise density of ~ 20 ppmv/ $\sqrt{\text{Hz}}$.

Figure 2F: Measured absorbance at a fixed water vapor mixing ratio as a function of total cell pressure. The absorbance has been normalized to the measured value at 1 atm pressure

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3. FIELD INSTRUMENT DESIGN AND CALIBRATION

In preparation for a field demonstration and to further the development of the water vapor monitor as a commercial instrument, the breadboard version of this sensor was re-assembled into a field prototype unit that incorporated the following significant improvements:

- Redesign and construction of new magnet and shield assembly to reduce fringing fields and improve mechanical mounting of magnets
- Replacement of twisted-nematic liquid crystal with a ferro-electric device increasing optical modulation rate to ~100 Hz, enabling higher speed measurements of water vapor
- A light-weight, low-cost, fiber-pigtailed multiple-pass cell was integrated into the instrument assembly
- Implementation of a custom-designed, rack mountable package to enable temperature stabilization of multi-pass cell and improve instrument versatility and appearance

Calibration of the instrument was accomplished using a mid-infrared (lead-salt) tunable diode laser system in a similar manner to the previous calibration¹ of the laboratory instrument, but in this case using water vapor samples produced by a NIST traceable dew point generator manufactured by Licor Inc (Model # LI-610). Data obtained at various water vapor concentrations and pressures were fit to polynomial functions to develop empirical formulae representing the instrument calibration. The polynomial expressions were then entered into the instrument control software to provide a real-time calculation and display of measured water vapor data in the field. The instrument calibration formulae, once determined at Aerodyne, were the same used throughout the duration of field measurements. The following sections provide further technical detail on the field prototype instrument.

3.1 Lamp Magnet Design

Many of our initial tests were done with a permanent magnet that consisted of stacks of NdFeB magnets between 3" diameter disks made of 416SS. The lamp was inserted into a plastic tube through the center of this, which provided electrical insulation for the anode. This arrangement was generally satisfactory except in two respects: it used more of the relatively costly rare-earth magnet material than would be necessary in a more efficient design, and it had a large fringing field, several hundred gauss at the front panel of the instrument. This last factor is especially troublesome in an instrument that may ultimately be used in the limited space available on a remotely piloted aircraft, where it could cause errors in the magnetic compass, for example. In view of these problems, a better shielded magnet was designed.

The magnet design was done using a finite element magnetostatic modeling program, Maxwell-2D (Ansoft, Pittsburgh, PA). An axisymmetric geometry was analyzed, as shown in Figure 3B. Note that in this geometry, the left hand edge of the figure is the axis of symmetry; the lower edge of the figure is a mirror image plane, and thus what is shown is one quadrant of a slice through the axis of the magnet.

In this model, the outer and inner shields, shell, poles, and inner flange are assumed to be made of 416 stainless steel. The Kovar tube that is brazed to the alumina is assumed to have magnetic properties similar to 416SS. The outer flange and (copper) gasket are nonmagnetic, as are the window, alumina tube, and capillary (denoted Cap. in the figure). The region inside the capillary divided into small rectangles is the region where the plasma resides; by subdividing this region, the numerical model is forced to use a smaller grid size than would be the case otherwise, thus improving the spatial resolution. The gap between the inner pole and the flanges again allows for the insulating tube that isolates the anode electrically. The assumed magnet material is NdFe35, a standard alloy. However, we do not actually know the exact specifications of the off-the-shelf magnets that were used here, and this probably explains most of the difference between measured and calculated field strength, as discussed below.

Figure 3A: Left photograph shows the overall view of the lamp and magnet. A 25 cent coin shows the size scale. Right photograph shows the magnet with two shields removed.

Figure 3B: Model of the lamp and magnet as used in numerical design.

The poles of the magnet are hexagonal, as seen in Figure 3A. Since the modeling program only handles 2 dimensional (axisymmetric, in this case) geometries, the poles were approximated as cylinders having the same surface area as the actual hexagons. Then, the length of the assumed cylindrical magnet was adjusted to make the volume of magnetized material equal to the actual volume of the discrete magnets used here.

The object of the two shields is to minimize the leakage of fringing fields from the ends of the magnet, while at the same time not excessively shunting the available field from the magnet. The partitioning of the shields shown in the figure is for convenience in adjusting their dimensions in the course of numerical design: the actual shape, as seen in Figure 3B, is a cylindrical wall capped by a plate. Similarly, the inner lining of the shell (below the outer pole in the figure), represents an adjustable wall thickness of the shell, that is selected to be no thicker than necessary to keep the wall material out of saturation. Note that if the wall material saturates, that causes a rapid increase in fringing field.

Once a suitable design had been arrived at by simulation, it was fabricated and characterized by measurements with a Hall effect probe. Figure 3C shows this comparison. As noted in the figure caption, the numerical model gave results that were about 10% high. This is believed to be chiefly the result of uncertainty about the exact properties of the magnets that were used, since when we probed the field in different geometries (with and without the shields, and with and without a break component having 416SS flanges), the ratio between measurement and model was consistently 0.9. [Our Hall probe has a specified accuracy of 0.25%, and in another project, measurement of the Zeeman effect of a spectral line of xenon showed agreement with theory within better than 1%.] Figure 3D shows a similar comparison in the central region of the lamp. As shown in Figure 3C, even along the axis of the lamp the fringing field beyond the end of the magnet's shield (at approximately 50 mm), is small and decreases rapidly. Measurements along a line parallel to the axis and tangent to the outside of the shell showed a maximum leakage of ~5 gauss. At the front panel of the water vapor monitor, any fringing field was below the ~0.1 gauss stability of our magnetometer.

Figure 3C: Comparison of measured field (o) with modeled field (solid line). The modeled field has been adjusted downward by a factor of 0.9.

Figure 3D: Comparison of measured field (o) with modeled field (solid line) in the central region of the lamp. The calculate field is adjusted downward by a factor of 0.9.

On the scale shown in Figure 3D, the capillary extends between approximately -15 mm and +10 mm. Thus, there is significant falling off of the field strength, especially at the far end. Basically, this is the result of the available breaks being only 0.75" long. As a result, some of the light emerging from the capillary has less-than-optimal splitting of the spectral line. However, the observed distribution of field strength can be incorporated into the calculation of the spectral distribution of the lamp output, from which the sensitivity of the water monitor is modeled.

3.2 Light-Weight Fiber-Pigtailed Multipass Cell

The cell used for this instrument is based on the off axis cavity type². Using a pair of toroidal mirrors, this type of cell can provide a high number of optical passes through a compact sample volume (0.3 liters) to maximize signal responsivity and minimizing gas volume turn-over time (increasing measurement response time for a given flow velocity). This type of cell has been used extensively in mid-infrared tunable diode laser instrumentation at Aerodyne³ and is manufactured as a commercial product by New Focus, Inc (model # 5611). However, the expense and heavy weight of these cells make them unattractive for use in a low-cost, compact instrument, and therefore two approaches were identified. The first, less risky approach, was to use the existing commercial design but adapted to accept a fiber-optic interface, while the second approach, considered more attractive but higher risk, was to utilize dielectric coated eyeglass substrates designed to fit a simple assembly that would significantly reduce the weight and cost of the instrument. Construction and laboratory testing of both approaches indicated the high risk approach could be successfully employed, and therefore the low-cost light-weight version of the cell was implemented in the field prototype.

Figure 3E is a schematic showing the details of the cell assembly. Mirrors for this cell were fabricated from astigmatic glass substrates supplied by an eyeglass manufacturer and treated with a high reflectivity dielectric coating to provide high transmission efficiency. Specifications for the radii of curvature are determined by surveying the available spot patterns that minimize beam spill-over on the mirror edges and entrance aperture for a given input beam diameter. The mirrors are aligned using a pair of gimbal mounts mounted on translation stages to adjust tilt, rotation, and spacing to arrive at the desired spot pattern, which is viewed using a

CCD camera and a 20 mW multi-mode laser (~ 905 nm operating wavelength). The selected spot pattern corresponded to 86 passes, a photograph of which is shown in Figure 3F.

Assembly of this cell is accomplished by first aligning the mirrors to the desired spot pattern, then fitting the mirrors to a stainless steel 2" diameter tube that contains gas fittings. This tube has welded end caps that contain 45 degree bevel edges that mate to ring mounts that hold the mirrors. One of the end caps has a threaded insert with an o-ring seal that enables fine adjustment of the length of the tube assembly to obtain a precise match to the correct mirror spacing. Once the mirrors are correctly aligned and fitted with the tube, high strength epoxy is used to permanently fix the mirrors to the tube, resulting in a robust cylindrical assembly weighing less than 1.5 lbs. that is ~ 11 " in length and 2" in diameter. Fiber-optic fitting coupling to the cell is accomplished using a single lens element that is inserted into the cell mirror aperture and mounting the input and output fibers in close proximity to the lens element.

Two multi-pass cells were constructed for the field tests. Each cell employed mirror substrates that had been coated with dielectric coatings from different suppliers. Cell #1, aligned to provide 86 passes (~ 18 meter path length), exhibited a degraded optical transmission when stabilized at the desired operating temperature of 37 degrees Celsius, and consequently exhibited a higher noise level of ~ 40 ppmv/ $\sqrt{\text{Hz}}$ (dry-air flow). Cell #2 exhibited a noise level of ~ 10 ppmv/ $\sqrt{\text{Hz}}$, but could only adjusted to a beam pattern of 110 passes (~ 23 meter optical path) due to a fabrication error in the machining of the substrates. Consequently, the signal-to-noise performance of Cell #2, while superior to Cell #1 at low water vapor concentrations because of increased light throughput, degraded faster at high end of the concentration range ($> 10,000$ ppmv) due to the more rapid attenuation of the light beam caused by absorption of water vapor in the longer optical path length. In view of these limitations, Cell #1 was designated as the primary measurement cell; most of the calibration work was done with this cell. Since the changeover between cells was greatly facilitated by the use of fiber-optic connectors, both cells were actually used during the field trials. As discussed in subsequent sections, both cells yielded good performance in the field when compared to other measurement instruments.

Figure 3E: Schematic of low cost, light-weight, fiber-pigtailed multi-pass cell

Figure 3F: Photograph of multi-pass spot pattern of the 86 pass cell when illuminated with a 905 nm laser source.

3.3 Field Instrument Layout And Custom Chassis Design

To assist in the mechanical layout and design of the field version of the instrument, the services of a mechanical design firm, Loeffler-McConkey, Inc., were employed. The resultant field prototype is a rack mountable 19" x 10" instrument package 6" in height that weighs less than 15 lbs, consumes less than 40 watts, with a total component cost of less than \$6,000. Figure 3G shows a mechanical drawing of the instrument used for field trials. This design consisted of a "dual" module chassis that housed the multi-pass cell in a separate compartment from rest of the instrument opto-electronics. The separate cell compartment enabled temperature stabilization of the multi-pass cell and, if desired, this section could also be detached from the rest of the instrument. This modular design therefore enables this instrument to be configured with a multi-pass cell placed remote from the opto-electronics module. As a result, in-situ measurements of water vapor could be obtained in future versions of this instrument, by placing the cell outside the aircraft in the free air stream, with a fiber-optic connection to the opto-electronics mounted inside the aircraft.

3.4 Chapter References

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2. J.B. McManus, P.Kebabian, and M. Zahniser, Applied Optics, **34**, 3336 (1995)
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Figure 3G: Mechanical drawing of the top view (top) and front panel (bottom) of the Aerodyne water vapor monitor.

4. FIELD TEST DESCRIPTION, AIRCRAFT INSTALLATION AND INSTRUMENT DIAGNOSTIC MEASUREMENTS

4.1 Test Description

During the month of August 1998, the Aerodyne Water Vapor monitor was successfully flight tested on the Gulfstream-1 Twin Turboprop Aircraft (G-1) operated by Battelle Memorial Institute and the Pacific Northwest National Laboratory as part of the Department of Energy's Shortwave/Aerosol Intensive Operating Period (IOP) field exercise. The IOP measurement plan emphasized flights over the ARM site near Lamont, OK in "clear-air". An essential part of the IOP measurement objectives was to compare aircraft aerosol measurements with those derived from the ground-based Raman Lidar. The Raman Lidar also represents the most significant tool available determining the 3-dimensional distribution of water vapor over the ARM site. Special balloon-borne sondes would also be launched as part of the IOP. The Raman Lidar and the sondes represent valuable "ground truth" for our water vapor sensor as well. Although the emphasis in the IOP was on clear air, many flights actually proceeded in partly cloudy conditions, with the objective of making measurements in the clear spaces between clouds.

The G-1 (see Figure 4A) was the most appropriate platform for demonstration of the Aerodyne water vapor monitor. In addition to a wide variety of cloud micro-physics, radiometric, and meteorological instrumentation, a chilled mirror hygrometer that provided a slow response (~ 10 seconds) absolute measurement of water vapor content, and a Lyman-alpha probe that provided an uncalibrated signal that responded to rapid (~ 10 Hz) water vapor fluctuations. Both of these instruments had sensor probes that were mounted outside the G-1 in the free air stream. The Aerodyne water vapor monitor, as a late add-on to the IOP instrument suite, had to be mounted inside the G-1 fuselage and employ a less than ideal air stream sampling system for rapid water vapor measurements (see Figures 4A and 4B). Details of the air sampling system used are described in the following section (see Section 4.2).

Installation of the Aerodyne instrument on the G-1 took place at the Pacific Northwest hanger facility in Pasco, WA in time for the shake-down test on 5 August 1998 (flight #1). The water vapor monitor was then transported with the G-1 to the Ponca City Municipal Airport in

Figure 4A: Photograph of the Gulfstream-1 Research aircraft at the Ponca City Municipal Airport after returning from an IOP flight (top) and view of the window plate inlet and exhaust ports used for the water vapor monitor (bottom).

Figure 4B: Photograph of the water vapor instrument, data acquisition, and gas handling set-up installed on the G-1.

Oklahoma on 10 August 1998 for the Shortwave/Aerosol IOP operations and collected data for an additional 8 flights (flights 2-9). A typical flight pattern consisted of taking off from the Ponca City Municipal airport, flying at low altitude to the Southern Great Plains (SGP) Central facility, and then flying back and forth in the same straight line track at multiple altitudes above the SGP exercise area. Increases in altitude would occur during the 180 degree turns at the ends of the straight line tracks. After reaching the maximum altitude (13,000 to 17,500 feet), the aircraft would then descend in a spiral pattern circling about the SGP central facility to a low altitude before returning to the Ponca City airport. Each flight was approximately 2 hours in duration, and water vapor variations were observed flying both in clear-air conditions and through clouds.

Data acquisition and display consisted of a laptop computer that recorded measurements at sampling rates from 2-4 Hz. Over 160,000 water vapor values were recorded for the duration of 9 different flights representing a total of 16 hours of flight data. Water vapor measurements recorded during flight ranged in dew point from -35 to 25 deg. C, corresponding to a range in water vapor concentration from 900 to 30,000 ppmv. In addition to collection of data during the flight tests, noise and calibration performance of the Aerodyne instrument was monitored and recorded on a daily basis prior to or after each flight using a dew point generator and a dry air source. The following sections provide additional detail on the inlet sampling system and diagnostic measurements used in the field to check system performance.

4.2 Air Sampling System

The Aerodyne water vapor instrument, given its optical absorption measurement technique, is inherently a high speed sensor; it is capable of providing sampling rates of 100 Hz or more if so desired. In the configuration used on the field tests, instrument response was actually limited by the rate at which the delivered airstream flowed through the optical absorption cell. A reasonable criterion to employ, given the nature of turbulent flow, was to ensure that the cell was flushed out approximately three times during a time period equivalent to the time response of the instrument. This assured that there was less than a 10 % carryover between measurement samples. The designed time response of the instrument for the field tests on-board the DOE Gulfstream aircraft was therefore set at 1 second; this value was deemed an acceptable compromise between the desire to measure water vapor fluctuations on as fast a time

scale as possible and the constraints on time and effort which could be employed in designing an elaborate air sampling system

In order to measure the effective flow rate through the inlet assembly and water vapor sensor, a mock-up version of the inlet system (using several meters of $\frac{1}{2}$ " diameter tubing connected to the absorption cell) was tested in a laboratory at Aerodyne using a pressure blower with flow conditioning. This apparatus was capable of producing effective air speeds of more than 100 m sec^{-1} over a $5 \times 10 \text{ cm}$ rectangular area. Figure 4C presents the results of these measurements. Note that at one atmosphere ambient pressure, a ram speed of 100 m sec^{-1} , the expected flight speed on the DOE mission, a volumetric flow of $\sim 0.8 \text{ liters sec}^{-1}$ through the absorption cell was measured. Also shown is the pressure drop across the sensor multiple pass cell. The pressure drop across the cell was $\sim 40 \text{ Torr}$ compared to the 50 Torr generated at ram speeds of 100 m sec^{-1} . This limiting pressure drop was caused by the connections to the cell, which were made using $\frac{1}{4}$ " VCO fittings which served as the limiting flow orifices (0.18 " diam.) in the entire gas handling system. The actual time response of the system was confirmed in the laboratory using an air flow of $\sim 0.8 \text{ liters s}^{-1}$ and alternating between flows with both high and low relative humidity. Figure 4D shows the result obtained when a pulse of high water vapor content, approximately 10 seconds in duration, was introduced into the sampling system. Note that the analysis of the leading and trailing edges of the transient indicate that the instrument performance approaches the desired goal of one second response time. Data recorded during flights indicated that volumetric flow typically exceeded 1 liter/second, resulting in a response time of less than 1 second.

The water vapor/air sampling probe installed on the G-1 consisted of a $\frac{3}{4}$ " o.d. stainless steel tube that passed through the fuselage wall and intercepted the ram airstream at approximately 9 cm distance from the fuselage wall. As shown in Figures 4E and 4F, the airstream that originated in this sampling probe was divided by using concentric inner and outer tubes that were diverted to the water vapor sensor and bypass line respectively. The intent of this arrangement was to minimize the sampling of air/water vapor that originated from any boundary layer that occurred in the sampling probe and to minimize the possibility of particles and dust from entering the water vapor sensor. Both the main and bypass flow tubes were

Figure 4C: Measured volumetric flow rate at atmospheric pressure of the water vapor sensor as a function of ram air speed as measured in the laboratory. Also shown is the pressure drop across the water vapor cell measured using a capacitance manometer.

Figure 4D: Laboratory measurement of instrument response time (left) for a pulse of high water vapor content air (~ 1.2 % water vapor, ~ 10 seconds in duration) at a flow rate of ~ 0.8 liters/sec. Plot on the right shows the normalized rise (inverted) and fall edges of the pulse, illustrating the closely matched shapes of the system time response. Flow rates through the cell obtained in flight typically varied between 1-1.5 liters/sec, resulting in a system response time of approximately 1 second.

Figure 4E: Schematic of the air inlet set-up used for the Aerodyne water vapor monitor.

Figure 4F: Gas handling set-up used for the Aerodyne water vapor monitor on the G-1.

constructed of 1/2" o.d. copper tubing. Further connections of the sampling lines to the water vapor sensor were constructed using brass Swagelock™ fittings and polyethylene tubing. Tubing within the aircraft were wrapped with heating tape and insulation and maintained above 30 °C. The main air flow was maintained at $\sim 37 \pm 0.5$ °C by passing it through a gas warmer (Air Products, operated at 120 volts and 0.5 amperes) that was linked to a power controller (MINCO) using a thermocouple to sense the gas temperature. Both the main air and bypass flows were exhausted through tubing and an exhaust duct that was similar to the inlet duct except that it was pointed 180° from the ram direction. Although not shown, a mixing manifold was also incorporated into the set-up that enabled air samples to be passed into the system from a dew point generator, ambient cabin air, or dry air source (produced from a column of desiccant) to enable additional testing of the water vapor monitor while installed on the Gulfstream-1.

4.3 Field Diagnostic Measurements

During field installation and flight testing of the ARI optical water vapor monitor, diagnostic measurements were obtained to quantify instrument noise level and repeatability of calibration. This was accomplished using a dry-air source and portable dew point generator (Licor LI-610) to flow sample air streams through the water vapor instrument. Results obtained for these diagnostic measurements as well as flight measurements are based on the instrument calibration implemented at Aerodyne prior to shipment of the instrument, and the Licor dew point generator provided a convenient way to confirm instrument repeatability.

Figure 4G shows the measured water vapor concentration response recorded (for the 86 pass cell) on seven different days. The results for the first 3 days (8/3-8/5) were obtained at the Pacific Northwest National Labs hangar facility in Pasco, Washington during preparation of the aircraft for the Shortwave/Aerosol IOP. The results shown for the remaining four days (8/11 – 8/15) were obtained during the ARM Shortwave/Aerosol IOP, after the aircraft was relocated to the Ponca City Municipal airport. As can be seen, the instrument response to known levels of water vapor was, as expected, highly repeatable during the course of installation and field measurements, with a peak deviations less than ± 3 % for the range of water vapor concentrations (~ 6000 to 28,000 ppmv) produced by the dew point generator. The exact cause of this small level of variability is not known at this time, but could be explained by a

Figure 4G: Result obtained when using a Licor dew point generator to verify instrument response in the field. Slight deviation above 25,500 ppmv is attributed to fitting limitations in the non-linear instrument response at high concentrations. Peak variation in repeatability was less than $\pm 3\%$ when using multi-pass cell #1.

combination of factors including issues with the use of the dew point generator when operated in the field. A more detailed laboratory-based investigation and environmental testing of the water vapor monitor would be needed to identify any residual temperature contributions from individual optical components.

In addition to repeatability measurements, instrument noise level was recorded over a range of water vapor concentrations using a dry-air source and the dew point generator. The table in Figure 4H is a summary of the instrument noise level recorded in the field when a dry-air sample gas stream ($< 0.02\%$ water vapor by volume) was flowed through the system. The day-to-day average dry-air noise level using cell #1 was $48 \text{ ppmv}/\sqrt{\text{Hz}}$ during installation in Pasco, WA and $40 \text{ ppmv}/\sqrt{\text{Hz}}$ during the initial part of the IOP exercise in Ponca City, OK. A second cell, using a 110 pass spot pattern with better transmission properties, was installed for the last three days of measurements, and exhibited an improved noise level $\sim 11 \text{ ppmv}/\sqrt{\text{Hz}}$. Dry-air measurements were also obtained while in flight using the 110 pass cell. As can be seen, instrument noise while in flight matches the approximate noise level observed when the aircraft is stationary, indicating that aircraft vibration and noise levels during normal operation do not negatively affect the performance of the water vapor monitor.

Instrument noise level was also recorded at different water vapor concentrations using the dew point generator. The water vapor monitor noise level has a non-linear dependence on signal level as the optical depth of the water vapor line increases to high values reducing the cell transmission. Figure 4I shows typical noise curves recorded as a function of concentration for both the 86 and 110 pass optical cells during field operations. For the majority of the instrument operating range (and typical concentration ranges present during flight testing), the second cell (110 passes) provides a significant improvement in noise performance during field measurements. At the highest concentrations however ($> 20,000 \text{ ppmv}$), the noise level exceeds that of the 86 pass cell, as its longer optical path gives rise to a higher optical absorption line depth for the same concentration. Although the noise performance at high concentrations was more than adequate for field demonstration of this instrument, the signal-to-noise performance of the instrument can be enhanced by optimizing the multi-pass cell optical path length to a specific concentration range. In the configuration reported here, the instrument was capable of measuring water vapor concentrations over 3 orders in magnitude.

	RMS noise (1 Hz bw)
<u>Cell #1 (86 passes):</u>	
Pasco (during aircraft installation)	48 ppmv
Ponca City (during IOP exercise)	40 ppmv
<u>Cell #2 (110 passes):</u>	
Ponca City (during IOP exercise)	10 ppmv
In Flight (during IOP exercise)	11 ppmv

Figure 4H: Instrument noise levels observed in the field for cells #1 and #2 when a dry-air gas flow is passed through the water monitor. Each value reported is the average result of 3 independent measurements that occurred during field installation and testing. The last result was obtained by passing a dry-air stream through the system when the aircraft was in flight, demonstrating that the instrument was not adversely affected while the aircraft was in operation.

Figure 4I: Instrument Noise level observed for cells #1 (86 passes) and #2 (110 passes) as a function of water vapor concentration.

5. FLIGHT DATA: INSTRUMENT INTERCOMPARISON

5.1 Comparison With The Chilled Mirror And Lyman-Alpha Sensors

The Aerodyne water vapor monitor collected data on nine different flights of the Gulfstream-1 (G-1) aircraft. A table summarizing the details for each flight is shown in Figure 5A, describing flight duration, air sampling and data acquisition settings, as well as maximum and minimum values for the Aerodyne measurements. Also shown are the number and peak magnitude of liquid water transients observed for each flight, representing the degree of cloud activity. A discussion of the system response to liquid water transients will be presented in Chapter 6. Analysis of data focused on flights #2-9, which took place over the ARM Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site near Lamont, Oklahoma. Instrumentation on the G-1 included a chilled mirror hygrometer manufactured by General Eastern (Model # 1011B) and a Lyman-Alpha hygrometer manufactured by Atmospheric Instrumentation Research (AIR). Sampling probes for both of these instruments were mounted outside the aircraft in the “free” air stream. An intercomparison of these instruments with the Aerodyne measurements is the main focus of this section.

Water vapor values obtained during the series of flights varied from -35 to 25 deg. C in dew point, corresponding to a range in water vapor concentration from 900 to 45,000 ppmv. Ambient temperatures ranged from -15 to 35 degrees Celsius. Although the Aerodyne water vapor monitor was initially calibrated in mixing ratio by volume (ppmv), an equivalent value in dew point was calculated from the measured pressure of the air sample¹ enabling comparison with the chilled mirror hygrometer data set. However, the chilled mirror measurement is based on equilibration of water on a surface, and is presumed to measure frost point when reporting a value below zero degrees Celsius. Values reported by the chilled mirror hygrometer in the frost range were therefore converted to an equivalent dew point value to provide a uniform scale over the full range of water vapor values and to facilitate direct comparison with the Aerodyne data.

Figure 5B shows the resultant water vapor values in dew point obtained from the chilled mirror (blue) and the Aerodyne (red) measurements for the duration of each of the flights (#2-9) during the IOP exercise. As can be seen, there is good over-all agreement between the two

Aerodyne Water Vapor Instrument: Gulfstream-1 Flight Test Data

ARM IOP Exercise, SGP CART field site (near
Lamont, OK)

Shake-down test (Pasco, WA)

Flight #	1	2	3	4	5	6	7	8	9
date	Aug. 5	Aug. 11	Aug. 13 #1	Aug 13 #2	Aug. 14	Aug. 15	Aug. 16	Aug. 17	Aug. 18
Flight									
duration, min	34.5	116.1	138.6	104.5	129.9	112.9	125.6	108.4	106.7
max.altitude, feet		13752	17637	13633	12570	17644	17080	17087	15527
Data Collection									
sample rate, Hz	2	2	2	2	2	2	2,20	4	4
lock-in, msec	100	100	100	100	100	100	10,100	10	10
Sampling System									
cell (pass number)	86	86	86	86	86	86	110	110	110
blower	off	off	off	off	off	off	on,off	on	on
by-pass	open	open	open	open	closed	closed	opn/clsd	closed	closed
flow rate, lit/sec	1	1	1	1	1	1	1/1.5	1.5	1.5
% water vapor									
max	1.6	2.5	2.6	2.3	2.7	2.1	4.6	3.3	2.5
min	0.51	0.7	0.18	0.75	0.47	0.12	0.09	0.1	0.12
Dew point, deg. C									
max	12.6	19.5	20.8	19.1	19.1	17.6	25.45	20.5	20
min	-6.8	-5	-23.3	-4	-9.4	-26.7	-35.9	-28.9	-27
Liquid water events									
#		36	5	0	23	16	34	9	0
peak g/m ³		1.9	0.3	0	1.3	0.3	1.19	0.4	0
sample rate, Hz		1	1	1	1	1	100	100	100

Figure 5A: Summary of flight information for the field demonstration of the Aerodyne water vapor monitor.

Figure 5B: Data obtained for the IOP exercise flights, comparing of Aerodyne dew point (red) with chilled mirror hygrometer(blue).

instruments for all of the flights. Significant differences (i.e. > 1 deg. C) typically occurred between the two measurements when water vapor changes exceeded the response time of the chilled mirror hygrometer (~ 10 seconds). There are some additional anomalous effects, most notably occurring on the 13 Aug (a) flight at $\sim 17:28$ (GMT) and on the 15 Aug flight at $\sim 20:25$ (GMT), and a more detailed analysis of the residual differences will be presented later in this section.

Figure 5C shows a more detailed view of water vapor data collected during the 17 Aug. flight, along with aircraft altitude and data from the Lyman-alpha probe. An absolute value was not available from the Lyman-Alpha instrument and therefore its raw voltage output (arbitrary water vapor scale) is shown offset to the chilled mirror and Aerodyne data. As can be seen, the highest water vapor concentrations are observed at the beginning and end of each flight when the G-1 was at a relatively low altitude, with the lowest water vapor concentrations at the peak altitude, occurring near the mid-point of each flight.

The Lyman-Alpha measurements were useful for monitoring rapid (< 10 second) changes in water vapor, and the examples in Figure 5D show expanded views of two different water vapor transients when compared to Aerodyne measurements. In both of these examples, the chilled mirror hygrometer is unable to resolve the true shapes of the water vapor structure observed by both the Lyman-alpha and Aerodyne instruments. As discussed in an earlier section of this report (see Section 4.2), the response time of the water vapor monitor was limited by the flow rate through the cell (~ 1 second), and therefore some of the fine temporal structure observed by the faster response (10 Hz) of the Lyman-alpha probe is not recovered by the Aerodyne measurement. Future versions of this instrument will incorporate a flow design that will permit measurements on the order of 10 Hz. The examples in Figure 5D clearly illustrate the ability of the Aerodyne water vapor monitor to combine two important features in one instrument: the ability to measure rapid water vapor fluctuations (consistent with Lyman-Alpha) and yield accurate absolute information (consistent with the chilled mirror). Similar agreement between the Lyman-alpha data and Aerodyne measurements to fast water vapor transients (outside of clouds) was observed throughout all of the flight data sets.

FIGURE 5C: Flight data recorded on 17 Aug., showing Aerodyne measurement (red), chilled mirror (blue), Lyman-alpha (green), and aircraft altitude (black). The Lyman-alpha data is shown offset to the other measurements.

FIGURE 5D: Aerodyne dew point (red), chilled mirror (blue), and Lyman-alpha (green) for measured water vapor transients observed at 15,800 feet on the 17 Aug. flight (left) and at 7,500 feet on the 15 Aug. flight (right). The Lyman-alpha data is shown offset to the other measurements.

To perform a more detailed comparison of the chilled mirror measurements to the Aerodyne data, a running box-car average of sufficient time duration (400 seconds) was applied to the water vapor data in order to reduce differences attributable to rapid fluctuations, but with an effective time constant short enough to maintain the over-all water vapor trend for each flight. Figure 5E shows the box-car averaged result obtained for the chilled mirror and Aerodyne measurements corresponding to the Aug. 14 flight data, illustrating the effect of the applied smoothing function. This same smoothing function was applied to all the other flight data from which an analysis of residual differences was performed.

Figure 5F shows the resultant correlation (X-Y) plots comparing the Aerodyne data to the chilled mirror as well as the corresponding difference plots. Over-all there is good agreement between the two sensors with dew point discrepancies typically falling within ± 1 degree C. Variations in the differences appear to be somewhat random above zero degrees C, but for the lower dew point measurements a systematic hysteresis effect appears. A possible explanation for this is in the assumption that the chilled mirror is reporting a true frost point at values below zero degrees C, which may not strictly hold for all conditions, as a super-cooled liquid water layer can form on the mirror surface prior to the development of a frost layer¹. If this occurs, the values reported by the chilled mirror with a super-cooled water layer will be artificially low with respect to the temperature measured assuming a frost layer, which is consistent with the trend observed in the data.

Figure 5G shows an expanded view time history in which this effect was most noticeable and previously identified at 17:30 (GMT) on the 13 Aug. flight. In this plot, the Lyman-alpha data are also shown and was arbitrarily scaled to match the over-all water vapor trend. As can be seen, the short-term relative changes in the Lyman-alpha data more closely match the Aerodyne sensor measurements, with the chilled mirror showing a significant deviation lower than the other two instruments at the initial part of level flight at $\sim 17,500$ feet. After a couple of minutes into level flight the chilled mirror returns back to the approximate value observed by the other sensors. Similar behavior was observed when climbing to and leveling off at peak altitude on other flights including, the anomaly observed at $\sim 20:25$ (GMT) on the 15 Aug flight.

Figure 5E: Result obtained when smoothing function is applied to the Aerodyne (red) and chilled mirror (blue) data sets for the 14 Aug. flight.

Figure 5F: Aerodyne data plotted against chilled mirror (smoothed data sets) for the IOP flights (top panel) and corresponding differences (chilled mirror minus Aerodyne) are shown in the bottom panel.

The table shown in Figure 5H is a summary of the statistical differences in the smoothed Aerodyne and chilled mirror data sets. The results for the two different cells (86 and 110 passes) are separated since different calibration formulae, accounting for the differences in optical paths, were utilized in calculating water vapor values. The slopes of straight line fits to the X-Y plot data for each flight shown in Figure 5F are reported in the first column of the table, representing the scale factor between the chilled mirror and Aerodyne data. The average slope of the first five flights using the 86 pass cell indicates a constant scaling difference of 5.8%, and a variation (1σ) in slope of 1.2% compared to the 110 pass cell reporting average 3% difference in scale factors and a variation of 1.5%. On average the 86 pass cell data set exhibited a small negative offset with respect to the chilled mirror while the 110 pass cell had a small positive offset. Statistics revealing the variability were approximately the same for both cells, a difference of 0.7 degrees Celsius, and exhibited higher numbers on the flights that exhibited the strongest hysteresis effects. Over-all these results represent excellent agreement with the chilled mirror hygrometer.

5.2 Chapter References

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Figure 5G: Time segment from the 13 Aug. flight #1, when deviation occurs between the chilled mirror and the results obtained from the Aerodyne and Lyman-alpha measurements.

	slope	average diff.	diff. st. deviation
Flight	(scaling coef)	(offset, deg. C)	(variability, deg. C)
86 pass cell			
Aug. 11	0.94303	0.69	0.465
Aug. 13 (a)	0.93004	-0.085	1.14
Aug. 13 (b)	0.95933	0.28	0.484
Aug. 14	0.94554	0.287	0.499
Aug. 15	0.93043	-0.1584	1.106
average	0.942	0.202	0.738
st.deviation	0.012		
110 pass cell			
Aug. 16	0.98036	-0.138	0.748
Aug. 17	0.99966	-1.05	0.612
Aug. 18	1.0102	-1.07	0.704
average	0.997	-0.753	0.688
st. deviation	0.015		

Figure 5H: Summary of statistical information obtained from the smoothed Aerodyne and chilled mirror data sets. The slopes of the best line fits to the correlation plots (see Figure 5F) are shown in the first column, the average differences representing the offset in deg. C are appear in the middle column, and the variability of the differences are reported in the right column.

6. ATMOSPHERIC PHENOMENA

6.1. Observation Of Atmospheric Phenomena

In addition to making useful comparisons with results obtained with the chilled mirror and Lyman-alpha hygrometers, these tests yielded a substantial data set revealing information about the behavior of water vapor during the field exercise. Figure 6A displays the results for all of the flights showing the mean (left panel) and standard deviation (right panel) values from the Aerodyne measurements for 1 minute data segments when the aircraft was flying at level altitudes. For altitudes below 6,000 feet, the day-to-day mean values follow a relatively stable trend while at higher altitudes the values increase in variability. The standard deviations also appear to be more stable at the low altitudes, but depart from any repeatable trend at a lower point in altitude when compared to the corresponding mean values. In general, the standard deviations in water vapor values are greater on flights (Aug 11, Aug. 14, Aug. 16) when clouds were present; however, there are examples of relatively large water vapor fluctuations in clear-air on flights with little or no cloud events, such as the variations observed at the highest altitudes for the flights on August 17 and 18. Measurements of water vapor at the edges of clouds by Perry and Hobbs¹, led to the concept of a water vapor halo surrounding convective clouds and related this effect to the dynamics of cloud generation and dissipation. Interestingly, the water vapor fluctuations observed during the ARM IOP flights in regions far removed from clouds were comparable in magnitude to variations observed on other flights when flying near clouds. This initial data set clearly illustrates the complex distribution of water vapor in the troposphere, and will need to be considered in context with other meteorological information.^{2,3}

Figure 6B shows a segment of the August 11 flight for the Aerodyne water vapor level (in % relative humidity) along with aircraft altitude, liquid water content measured by a Gerber probe from the G-1, and cloud base heights measured by from a ground based ceilometer stationed at the SGP central facility. The aircraft sequentially increased altitude from 4,000 to 14,000 feet and entered a broken layer of fair weather cumulus clouds at approximately 7,000 feet. The liquid water data shown provides a definition of cloud events, and typically coincides with values exceeding 100% relative humidity in the water vapor data. In the sampling configuration used on the G-1, the gas stream was heated to ~ 37 degrees Celsius prior to

FIGURE 6A: Mean (left panel) and standard deviations (right panel) obtained from the Aerodyne water vapor measurements for 1 minute data segments when flying at a stable altitudes.

FIGURE 6B: Data recorded during the 11 August flight, showing aircraft altitude and SGP ceiliometer data (top graph), liquid water content (middle) and Aerodyne water vapor (bottom). As can be seen the aircraft ascended into a broken cloud deck ~ 7,000 feet. Due to heating of the air sample, the Aerodyne measurement provides a measure of total water content (ambient vapor and vaporized liquid) and therefore will exceed 100% relative humidity when inside a cloud.

entering the water vapor instrument, thus the water vapor data reflects a measurement of total water content (ambient water vapor plus vaporized liquid water).

Expanded views of cloud events are shown in Figures 6C and 6D showing the measured dew point, ambient temperature, and liquid water content. In the first example, a relatively small ($\sim 0.1 \text{ g/m}^3$ pk) liquid water event is preceded by a series of significant (~ 4 degree changes in dew point) water vapor fluctuations. As expected, the dew point exceeds the ambient temperature when liquid water is present. There are two instances that appear prior to the arrival of this liquid water event when the dew point marginally exceeds ambient temperature, indicating the possible occurrence of super-saturated conditions outside of a cloud. However, the values above saturation are so small that they fall within instrumental offset uncertainties in temperature and dew point measurements and therefore the presence of super-saturation cannot be determined from this data.

The situation represented by Figure 6C in which significant fluctuations in water vapor occurred in the clear air when no cloud was present as well as in the air as a cloud was approached was common. Our initial atmospheric emphasis was focused on the water vapor structure surrounding clouds so that we might be able to evaluate the contribution of such water vapor to the so-called “anomalous absorption” of clouds.⁴ However, the unexpected occurrence of water vapor structure in clear air quite removed from clouds adds a new element of potential analysis and future research.

In the second example (Figure 6D), water vapor fluctuations are shown for a series of liquid water events that occurred between 19:15 and 19:18 (GMT) on the 14 Aug flight. Peak liquid water content for this series of events was 0.4 g/m^3 with individual liquid water transients corresponding with the Aerodyne data exceeding saturation, further confirming the presence of a cloud. This result also shows a high degree of water vapor variability outside clouds, ranging in dew point from a momentary drop to 7 deg. C, ~ 30 seconds prior to arrival of liquid water events, to 13 deg. C at $\sim 19:17$, near the mid-point of the time segment showing a water vapor value close to saturation. More detailed comparisons with the Lyman-alpha data in the presence of cloud transients, although not shown here, demonstrate excellent agreement with

Figure 6C: Data obtained flying at 5850 feet during the 14 Aug. flight showing strong variations in water vapor content prior to the arrival of a liquid water transient. Water vapor values prior to this event momentarily exceed saturation (ambient temperature), indicating the possibility of super-saturated conditions. However, the values above saturation are so small, they fall within the uncertainties in the temperature and dew point measurements.

Figure 6D: Data obtained while ascending through a broken layer of clouds at ~6000 feet during the 14 Aug. flight. The Aerodyne measurement shows strong correlation to the liquid water events observed by the Gerber probe, reporting dew point values exceeding ambient temperatures as a result of the vaporization of liquid water.

water vapor fluctuations when reporting values below saturation. Furthermore, time correlation analysis with the liquid water and Lyman-alpha data did not reveal any strong instrumental hysteresis effects in the Aerodyne data in the presence of liquid water transients.

In addition to the observation water vapor fluctuations in and around clouds, as noted earlier significant water vapor fluctuations were also observed in relatively clear portions of the atmosphere, far removed from clouds. Figure 6E shows an example of water vapor fluctuations observed on the 17 Aug flight along with the ambient temperature and liquid water data. As can be seen, fluctuations in water vapor as large as 4 deg. C in dew point were observed. Also evident is an apparent inverse correlation with the relative small changes in temperature recorded. This inverse relationship with temperature was also observed at other altitudes, in clear air as well as near clouds. The typical over-all trend observed in the flight data is a decrease in water vapor with temperature for an increase in altitude, more consistent with over-all lapse-rate trends attributable to adiabatic expansion of the atmosphere. The inverse water vapor-temperature relationship indicates the presence of a secondary mechanism that may be attributable to either a fundamental relationship between water vapor and temperature and/or the presence of meteorological wave features in the atmosphere.⁵ To identify the significance of the observed inverse temperature-water vapor correlation, further analysis of data will need to be considered in conjunction with other dynamical meteorological information.

6.2 Areas of Future Research and Data Analysis

These initial measurements (with more comprehensive analysis and interpretation) may yield additional insight into cloud physics, radiation transport and atmospheric dynamics.

Possible avenues of investigation include:

- Ground Truth for Raman LIDAR Measurements

Comparison of our water vapor data observations with Raman Lidar ground-based observations can serve as “ground truth” for the Raman Lidar. In turn, the Raman Lidar may serve to extend our in-situ measurements toward the creation of 3-dimensional water vapor case studies.

Figure 6E: Water vapor and temperature fluctuations observed in clear air during the 17 Aug flight when flying at ~17,500 feet.

- **Saturation Effects in Cloud Formation**

Comparison of our water vapor observations with aerosol measurements made by the IOP science team may yield further insights regarding saturation and super-saturation effects in cloud formation.

- **Aerosol Nucleation and Growth**

Comparison of our water vapor observations with on-board aerosol measurements may lead to a further understanding of the nucleation and growth of aerosol particles with changes in relative humidity.

- **Development of 3-D Models of Atmospheric Water Vapor Structure**

The observation of the anti-correlation of temperature and water vapor should be further explored to examine the implications in terms of atmospheric wave structure and dynamics. Following a more complete integration of the observations, it would be logical to develop 3-dimensional structure models of water vapor, both in clear atmosphere and near the edges of clouds. Such models can then be exploited as input to radiative transfer calculations to explore the implications of water vapor structure on atmospheric (and cloud) absorption and heating.

- **Anomalous Cloud Absorption**

The development of 3-dimensional models of cloud/water vapor should be evaluated in terms of the impact on visible/near-infrared absorption of solar radiation passing through convective clouds.

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7. COMMERCIALIZATION ASSESSMENT

(contributed in part by Foresight Science & Technology , Inc.

Report, dated September 21, 1998)

Aerodyne Research, Inc. conducts contract research and development in atmospheric and environmental chemistry, combustion and propulsion, materials technology, and optics and electro-optics. The company was founded in 1970 and is located at 45 Manning Road, Billerica, MA 01821. It has 50 employees. Revenues are primarily derived from research and development activities; in the last ten years, Aerodyne has also developed considerable cash flow from sales of both a line of trace gas monitors and simulation software. It is seeking to license its water vapor sensor, with a preference for exclusive licensing by product sector (market). Aerodyne is prepared to conduct instrument development for niche applications under a strategic alliance/licensing deal. It also will sell custom systems for R&D and other unique applications.

Aerodyne brings to commercialization of this technology three unique competitive advantages:

- Its technology is patented;
- It can draw upon a high caliber technical staff to adapt this technology to meet market needs; and for atmospheric applications,
- It possesses a deep scientific understanding of atmospheric phenomena and the application of optics-based technology to measuring these phenomena.

The water vapor sensor described in this report is ideal for measuring fairly high water vapor concentrations (up to saturation) at high pressures. The water vapor sensor operates as a mixing ration monitor so long as the ambient pressure is from 0.3 to 1.2 atmospheres. The instrument does operate below 0.3 atmospheres pressure, but loses sensitivity in that it becomes sensitive to the absolute number density of water vapor instead of the mixing ratio. Currently, the instrument sensitivity is ~10 parts per million by volume for a measurement bandwidth of

1 Hz. Improvements in the technology are expected to lower the threshold measurement value by at least a factor of three. In theory, the instrument can make water vapor concentration readings at rates up to a thousand times a second.

Application of this instrument in any number of harsh environments is generally not a problem because of the nature of the measurement technique and physical layout of the instrument. Fiber-optic coupling of the measurement cell to the controller unit containing all electronics and data acquisition modules allow for the remote placement of the measurement cell. This is important in situations where the in situ presence of any electrical equipment is not desired, either due to electrical spark hazard or the presence of harsh conditions that could be deleterious to the operation of electrical equipment. The most reliable measurements can be made in situations where the sample air stream can be heated to a constant temperature before it enters the measurement cell; however, if this is not possible, instantaneous correction due to temperature fluctuations can be made.

Two custom made devices (one for Department of Energy under the SBIR program and one for the Office of Naval Research) have been built with a parts cost of less than \$6,000. In production, these costs could be reduced considerably. Total productions costs, including labor could range from \$4,000 to \$6,000, depending on volume. The initial units have proven to provide quite stable and accurate readings, once calibrated. (For that reason, after the prototype is flown by DoE's ARM program, NIST has requested it for evaluation as a transfer standard.) The Aerodyne system offers one of the better alternatives for applications requiring high repeatability and capable of justifying higher prices within its accuracy ranges.

The market for this type of technology appears good. There are a number of low volume research-related uses. The first is meteorology. There is a need for a better high-end instrument for airport and other primary weather stations, such as NOAA's ASOS system. At present, NOAA is using chilled mirror hygrometers which have not performed as desired because of their requirement for frequent maintenance due to the dirty environment. Current emphasis in the ASOS program is being placed on the development of capacitive instruments, which while inexpensive, provide slow response and questionable long-term reliability. The Aerodyne Research water vapor monitor could also be of use at the NOAA Climate Monitoring and

Diagnostics Laboratory for tropospheric water vapor measurements. Its good time response, for example, could make it useful as an instrument flown on commercial airliners for measurement of upper tropospheric water vapor. Since an increase in water vapor, particularly in the upper troposphere, provides the primary positive feedback mechanism leading to global warming as a result human emitted greenhouse gases, this a significant area where additional knowledge is needed. The second application is as an aid for dry measurement stack systems. Forthcoming EPA regulations relating to acid rain deposition are likely to require enhanced moisture measurement. The third application is in food processing and monitoring.

One of the most favorable markets for the sensor involves its use as a calibration tool. Current low-cost moisture sensors drift and therefore require frequent re-calibration. The Aerodyne unit has potential as a transfer standard since it should provide stable and repeatable response. Transfer standards are used as references that can be sent to others as a calibration tool. For over 50 years, the only reliable transfer standard has been the chilled mirror hygrometer, which is a relatively simple and inexpensive (\$5,000-\$10,000) instrument with some recognized drawbacks (such as ambiguities in providing frost versus dew point measurements and a slow time response). Aerodyne's optical measurement approach should be equally repeatable and stable and not be subject to these drawbacks. Compared to chilled mirror technology and the use of prepared water vapor samples, the Aerodyne instrument provides a cost-effective option.

Hygrometers may be viewed as a sector within the Test and Instruments industry. There are approximately 100 companies (both large and small) making and selling hygrometers. Competition primarily involves price within niches that are defined by performance. The market is structured like a pyramid. Low performance, low price (~\$50) units comprise the bottom segment. At the top end are very high priced (~\$14,000), high performance (ppb) instruments. Near the top are instruments against which Aerodyne will compete. Foresight Technology estimates the overall market as between \$100 and \$300 million and the niche for Aerodyne at around \$20 million. Licensing revenues could approach \$1 million.

A two pronged approach to commercializing the Aerodyne Optical Water Vapor Sensor is recommended. The first tack involves aggressively pursuing R&D projects resulting in advanced versions of the sensor. This will allow Aerodyne to sell units while gaining R&D

revenues to enhance the system. For example, DOE has expressed interest in permanently installing a sensor on their measurement aircraft. Aerodyne should also seek funds from other Federal agencies. It currently has funding from the Office of Naval Research for delivery of a system, which has also pledged \$270K for aircraft flight time to support a proposed NSF project in collaboration with the California Institute of Technology.

The second approach is to vigorously pursue firms in the hygrometer industry to license versions of the sensor for industrial and atmospheric applications. In forming Phase III partnerships, Aerodyne would conduct applied research and engineering development, and, if necessary, some of the product engineering and customer support. The ideal partner would conduct manufacturing, sales, customer support, and product engineering. The preferred licensing partners would be chilled mirror hygrometer manufacturers who already possess significant market penetration.

8. CONCLUSIONS

The water vapor sensor developed by Aerodyne Research, based on the optical absorption of light at ~ 935 nm, has been successfully demonstrated on board the Pacific Northwest National Laboratory's Gulfstream-1 research aircraft during the Department of Energy's ARM Intensive Operations Period in August 1998. Data taken during this field campaign show excellent agreement with a chilled mirror and Lyman-alpha hygrometers and measurements confirm the ability to measure rapid, absolute water vapor fluctuations with a high degree of instrument stability and accuracy, with a noise level as low 10 ppmv (1 Hz measurement bandwidth).

The construction of this small, lightweight sensor contains several unique elements which result in several significant advantages when compared to other techniques. First, the low power consumption Argon discharge lamp provides an optical beam at a fixed wavelength without a need for temperature or precision current control. The multi-pass absorption cell developed for this instrument provides a compact, low cost method that can survive deployment in the field. Fiber-optic cables, which are used to convey light between the absorption cell, light source, and detection modules enable remote placement of the absorption cell from the opto-electronics module. Finally, the sensor does not use any moving parts which removes a significant source of potential malfunction. The result is an instrument which maintained its calibration throughout the field measurement campaign, and was not affected by high vibration and large uncontrolled temperature excursions.

We believe that the development of an accurate, fast response water vapor monitor described in this report will open up new avenues of aerial-vehicle-based atmospheric research which have been relatively unexplored due to the lack of suitable low-cost, light-weight instrumentation. These avenues include the exploration of water vapor perturbations in and around cloud formations and the role of water vapor in the nucleation and growth of aerosols. Planned upgrades for this instrument include attainment of high sensitivity (~ 3 ppmv/ $\sqrt{\text{Hz}}$) and implementation of a cell configuration to yield < 0.1 second system response times. The latter goal will require redesign of the air sampling system and sample measurement cell to provide higher air flow velocities. Eventually we hope to develop a truly remote sampling cell that will attach to outside the fuselage or wing of the aircraft.

APPENDIX I.

[Measurement Science and Technology, 9:1793-1796 (1998)]

Water Vapor Sensing Using Polarization Selection of a Zeeman-Split Argon Discharge Lamp Emission Line

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ABSTRACT

Water vapor concentrations are measured using the optical absorption of a Zeeman-split emission line of an argon discharge lamp. When a longitudinal magnetic field of the proper magnitude is used to split the emission line, two components of opposite circular polarization are produced: one coincident and one off-resonance with respect to a water vapor absorption line at $10,687.36\text{ cm}^{-1}$. Differential absorption is directly measured by alternately selecting the polarization of the light which is allowed to propagate down the optical path into a multi-pass absorption cell. Water vapor concentration measurements were obtained over a range of over three orders of magnitude (~ 0.002 - 3.0%). The monitor was also shown to act directly as a mixing ratio (mole fraction) sensor (within $\pm 10\%$) over a pressure range of 0.3 - 1.2 atmospheres.

The need for robust, low cost, compact instrumentation for the rapid measurement of water vapor concentrations over a wide range of conditions is an issue of great concern for both the atmospheric¹⁻³ and industrial sensing communities⁴. In particular, instruments are needed by atmospheric researchers for the measurement of water vapor in the troposphere and lower stratosphere using small manned and unmanned aircraft and aerial vehicles. Optical water vapor instruments can function far more rapidly and reliably than traditional instruments which rely on the equilibration of water vapor with a surface. In response to these needs, we have developed a novel water vapor monitor that utilizes optical absorption of an emission line emanating from a simple gas discharge lamp in the water vapor absorption band in the near infrared (~ 935 nm).⁵ The advantages of the gas discharge lamp, compared to the use of alternative light sources (e.g., near-IR diode lasers)⁶⁻¹⁰, are the stability and reproducibility of the spectral properties of the light, which results in a relatively simple and inexpensive instrument. It also offers significant advantages in range, speed, simplicity, size and low power consumption that cannot ordinarily be achieved by other types of sensors including chilled mirror, Fourier transform infrared absorption-based and Lyman- α hygrometers.

The lamp emission of interest is the neutral argon line at 935.4 nm wavelength ($10,687.43$ cm⁻¹).^{11,12} This line is known to be close to, but not coincident with, a strong water vapor absorption line at $10,687.36$ cm⁻¹; this line is the second strongest spectral feature in the 940nm water vapor absorption band.¹³ When the emission line is Zeeman-split¹⁴ by a longitudinal magnetic field of the proper strength, it is divided into one component that is strongly absorbed by the water vapor line, and a second component that is only weakly absorbed. Figure 1 presents a detailed simulation (calculated using HITRAN¹³) of the relevant spectral profiles of the water absorption line at an ambient pressure of 1.0 atmosphere and the split emission lines in a magnetic field of 1600 Gauss. As can be seen, Zeeman splitting of the emission line produces two components, one downshifted so as to overlap the maximum of the water absorption line, and one shifted to sufficiently higher frequency so as to ensure weaker absorption.

Another useful property of the Zeeman-split lamp line components is that they possess circular polarizations of opposite handedness. If the succeeding optical train is designed to discriminate between these polarizations, the ratio of the differential absorption of these components to the off-resonance component, $\Delta I/I_0$, can be used to determine the column density of water vapor in an open- or closed-path absorption cell. This can be accomplished by allowing the light to pass through a quarter wave plate, which converts the two circular polarizations (of opposite handedness) to orthogonal linear polarizations. The light then passes through a liquid

crystal rotator and linear polarizer element, such that when the appropriate drive signal is applied to the liquid crystal, the output is alternately switched between the two different polarization states. The modulation frequency of the measurement is limited by the frequency at which the liquid crystal cell polarization is switched. Modulation frequencies greater than 1000 Hz can be achieved using commercially available ferroelectric type devices.

In order to demonstrate this approach, the optical system shown in Figure 2 was constructed. The argon discharge lamp used in these experiments (shown in Figure 3) was assembled from ultrahigh vacuum components. The active plasma volume of the argon lamp is defined by a glass capillary tube (2 mm i.d., 25 mm long) which fits tightly in the bore of an insulating break (i.e, an alumina ceramic section brazed to Kovar spool pieces with 3.37 cm o.d. 400 series stainless steel knife edge flanges attached). At one end of the break, a flange (functioning as the anode of the lamp) with a Pyrex™ window acts as a light port. At the other, the capillary extends into a tee fitting, lined with aluminum, that serves as the cathode of the lamp. An annealed copper tube, attached to the side arm of the tee, is used to fill the lamp with 3 Torr of ultrahigh purity argon. This tube is then pinched off to make a high-vacuum seal. A non-evaporating zirconium alloy getter, attached to the other port, removes trace impurities in the argon fill. The lamp operates at ~200 V and 4 mA; power is provided by a switching power supply commonly used with He-Ne lasers.

The lamp is equipped with a magnetic circuit consisting of steel flanges which extend the diameter of the flanges to ~7.5 cm, between which stacks of Nd-Fe-B permanent magnets are located. Since the insulating break is constructed from ferromagnetic materials, it too is part of the magnetic circuit. This particular design, which has the advantage of using off-the-shelf magnets, has been shown, both by model calculations and by measurement, to produce a uniform field over the region between the ends of the Kovar tubes attached to the alumina section. A magnetic field of 1600 Gauss was used in these experiments.

The light emitted by the argon lamp is collected by a lens (chosen to efficiently image the plasma volume while rejecting the light reflected from the tube walls) and sent to the polarization selection elements. In the configuration used here, a twisted nematic liquid crystal cell driven by a 5 Hz square wave is used to provide polarization selection. In order to reject unwanted lamp emission lines outside the 940 nm band of interest, the output is also sent through a narrow band interference filter. Light is then coupled to the multi-mode fiber, passed through a fiber-optic

splitter, which serves as a convenient optical tap for the reference detector, and into a multipass absorption cell. The 18 meter path length off-axis multipass absorption cell (86 passes) utilizes mirrors made of glass substrates with high reflectivity (>99.5%) dielectric coatings.^{15,16} The light output from the optical cell is coupled to a high-gain transimpedance photodetection circuit (Si detectors). Common mode noise caused by lamp intensity fluctuations is then minimized by subtracting the (scaled) reference detector signal from the sensor detector signal and sending the difference signal to a lock-in amplifier in order to recover the magnitude of the 5 Hz differential absorption signal. Measurement of water vapor concentration is achieved by normalizing the lock-in output to the DC component of the combined detector signal.

In the water vapor concentration measurements reported here, a gas flow of high water vapor content in air was manufactured using a bubbler arrangement; this stream was admixed with dry air (less than 1 ppmv water vapor content) to produce mixtures ranging from 30 to 30,000 ppmv water vapor content. The gas stream containing the water vapor was flowed at approximately 3 slpm (~ 0.13 moles min^{-1}) through the multipass absorption cell. Pressure and temperature in the cell were measured using a capacitance manometer (1000 Torr full scale) and a chromel/alumel thermocouple respectively.

In order to establish the water vapor concentration in the first cell (i.e., calibrate the sensor), the gas flow was then sent through a second multipass absorption cell which could be interrogated by a cryogenically-cooled lead-salt tunable diode laser (TDL) system which was operating at 1933 cm^{-1} . (Details of a typical TDL absorption spectrometer are given elsewhere.^{17,18}) This second cell was kept at much lower pressure (~ 20 Torr) in order to allow the TDL measurement to be made in the Doppler-broadened pressure limit. Under these conditions, the TDL system was capable of determining the water vapor content to a precision of 1 ppmv with $\sim 5\%$ accuracy (limited by the uncertainty in the absolute absorption strength of the observed line and errors in fitting the observed line shape). Although it is ideally suited for purposes of providing a water vapor content calibration instrument, the TDL system is too large and heavy and consumes too much power for use on small aircraft.

The observed absorbance $[-\ln(I_0 - \Delta I/I_0)]$ of the water vapor sensor versus water vapor concentration at atmospheric pressure is shown in Figure 4. Note that the absorbance versus concentration measurements are not linear above 10,000 ppm. This deviation from Beer's Law is characteristic of instruments in which the 'off-resonance' reference beam (I_0) actually overlaps the absorption feature of interest. Other factors contributing to the non-linearity are light leakage of

adjacent Ar spectral lines through the band pass filter and self-broadening of the water absorption line at higher water concentrations (i.e., the absorption cross section becomes dependent on the amount of water in the system). The noise floor exhibited by the sensor system was 3 ppmv r.m.s. for the 10 second lock-in filter time constant used which corresponds to an equivalent noise density of 20 ppmv/ $\sqrt{\text{Hz}}$ r.m.s.. Improvements in lamp output and optical coupling should improve this value significantly.

We also present data taken at one water vapor concentration (970 ppmv) over a range of pressures comparable to that found in the troposphere and lower stratosphere. Figure 5 shows that over a considerable range, ~ 0.3 -1.2 atmospheres (230- 900 Torr), the sensor acts as a mixing ratio monitor (i.e., measures the fractional water content, not the absolute number density) to within an accuracy of $\pm 10\%$. Pressure-independent behavior is typical of spectroscopically-based instruments which operate in the pressure-broadened regime (i.e., where, to first approximation, the water absorption cross section is inversely proportional to total pressure). The more complicated behavior demonstrated by this instrument at high pressure indicates that this approximation does not strictly hold. At the lowest pressures measured, the water absorption cross section becomes independent of pressure and the instrument responds directly to water vapor number density.

In conclusion, we have demonstrated that a water vapor sensor based on the optical absorption of an emission line of an argon discharge lamp can be used to determine a range of three orders of magnitude of water vapor concentrations. With the use of faster switching liquid crystal cells (up to 1 kHz) and development of brighter argon discharge lamps, 10 Hz measurements could be achieved over a range of water vapor concentrations which is consistent with the expected water vapor levels in the troposphere and lower stratosphere. Furthermore, the sensor effectively acts as a mixing ratio monitor from 1.2 atmospheres pressure down to 0.3 atmospheres. Its simplicity, small size, low weight and power consumption (10 W) make it ideal for the determination of water vapor concentrations (in either open or closed path configuration) in the troposphere and lower stratosphere using small manned and unmanned aircraft and aerial vehicles.

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Figure Captions

1. Computed absorption spectrum of water vapor in the 940 nm region (.....) at a total pressure of 1.0 atmospheres and the spectral output of an Ar discharge lamp with (—) and without (— —) the presence of a longitudinal magnetic field. Path length =18 m, $B=1600$ G, $T=295$ K, and $[H_2O]=1.3\%$ (~50% RH).
2. Schematic diagram of the water vapor sensor.
3. Schematic diagram of argon-filled discharge lamp.
4. Measured absorbance as a function of water vapor mixing ratio at a total pressure of one atmosphere in air at $T=295$ K.
5. Measured absorbance at a fixed water vapor mixing ratio as a function of total cell pressure. The absorbance has been normalized to the measured value at one atmosphere pressure.