The 2nd Generation Water Vapor Sensing System and Benefits of Its Use on Commercial Aircraft for Air Carriers and Society

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1. Introduction

The second-generation atmospheric water vapor sensing system (WVSS-II) is an aviation product for commercial and military aircraft. This instrument is a small, compact and efficient measurement system for determining water vapor mixing ratio using a diode laser (provided by SpectraSensors) and the flush mounted University Corporation for Atmospheric Research (UCAR) air sampler (patent pending). Mixing ratio values are measured directly and downlinked in real-time.

The extreme accuracy of the WVSS-II (research quality measurements in accuracy and precision) and the system's long lifetime (20 years) are due in part to the adaptation of the telecommunication industry diode lasers to the aviation measurement application. The use of single mode diode lasers for otherwise difficult measurement problems is **not new** (applications began over 20 years ago – see Appendix for a chronological summary of activity). The single frequency characteristics of the diode laser allow the measurement of a particular gas using a **single absorption line**, thus avoiding the interference from other gases in the same volume. This feature, coupled with further hardware and software enhancements described in Section 2, allows the accurate measurement of many gases, including water vapor – even in low levels of concentration.

Development of the flush mounted air sampler for commercial and military aircraft has been completed, tested and demonstrated. The design optimizes the combined use of the air sampler and diode lasers (and similar quantum cascade (QC) lasers for the measurements of frequencies in the mid-IR range). Details of the diode laser measurement system, the air sampler, and how the two components work together for an optimal measurement system are discussed in Section 2. Also included in Section 2 is a summary of the WVSS-II accuracy, precision, and testing activities. The operational aspects of the WVSS-II on commercial aircraft are summarized in Section 3. Information on power requirements, installation, and the very simple maintenance procedure are also included in this Section.

It is no longer just a cliché that we all share a single life sustaining atmosphere. With an ever-growing world population and more sophisticated commerce, our society has become immersed in stewardship activities for our atmosphere. The aviation industry has shared in this stewardship role through a variety of past programs and more recently in the real-time data gathering mode through the use of the Aircraft Communications Addressing and Reporting System (ACARS). The value of real-time winds and temperature data from commercial aircraft has already been demonstrated in Australia, Europe and the United States. **With the addition of the water vapor measurement, the commercial aircraft now have the potential to provide an extraordinarily more powerful contribution to the aviation industry and to society in general.** These benefits are included in Section 4.

This document, with figures, photos, and references, provides a concise summary of the WVSS-II, the expected migration of virtually identical hardware and software to the measurement of other atmospheric trace gases, and a brief review of the benefits of this technology to aviation and society as a whole. Further information can be obtained from the contacts listed on the inside cover.

2. The Proven Technology

2.1 Diode and Quantum Cascade (QC) Lasers

The WVSS-II uses a near-infrared diode laser to measure accurately the atmospheric water vapor mixing ratio. This was first proven on high altitude balloons and NASA research aircraft (cf. May, 1998). These first applications were "open path" systems with the laser beam extending through the open air beneath the balloon or aircraft. The measurement concept uses Beer's Law in the form:

$$I = I_o \exp(-\sigma\ n\ 1) \qquad (1)$$

where I = the laser light intensity at detector
I_o = laser initial intensity
σnl = absorbance
with n = number density of absorbing species
l = optical path length
σ = molecular absorption cross section, a function of pressure and temperature near the laser light path

In the usual application of the above formula, I and I_o are measured, σ and l are known, thus the number density (n) can be calculated from all the other available quantities. For increased detection sensitivity, thus higher precision and accuracy, second harmonic detection is utilized in which a small-amplitude wavelength modulation is added to the laser current (described in May, 1998 and in greater detail in May and Webster, 1993).

The measurement concept, technology, and software of the above scheme have been proven in numerous applications (see the 20-year history of these laser systems summarized in the Appendix and the test results of the WVSS-II in Section 2.3).

The diode laser manufacturing process is similar to that of a computer chip. The size of the diode laser assembly used in the WVSS-II is shown in Figure 1.

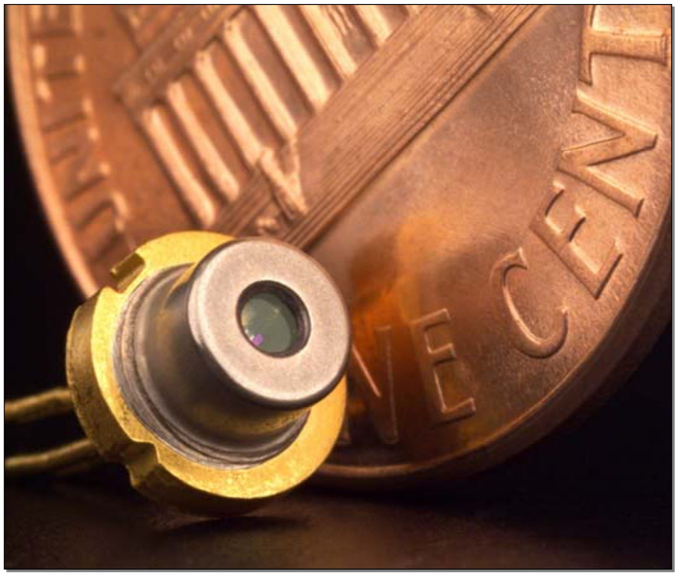


Figure 1. Diode laser.

SpectraSensors has incorporated similar lasers into their water vapor measurement system for the natural gas industry. The WVSS-II diode laser is identical to that used in the telecommunication industry. These lasers are "Telcordia (formerly Bellcor) certified (GR-468-CORE)", which is an industry standard similar to "FAA or CAA certification". These are the identical diode lasers used in the WVSS-II. **Their expected lifetime is 20 years.**

The laser signal received is detected by a standard InGaAs photodiode**.** Details on how the laser light source and the laser light detected are used for accurate water vapor detection are provided in Section 2.3.

The air sampler and the measurement cell (which physically houses the laser, receiver, and other sensors) are shown in Figure 2.

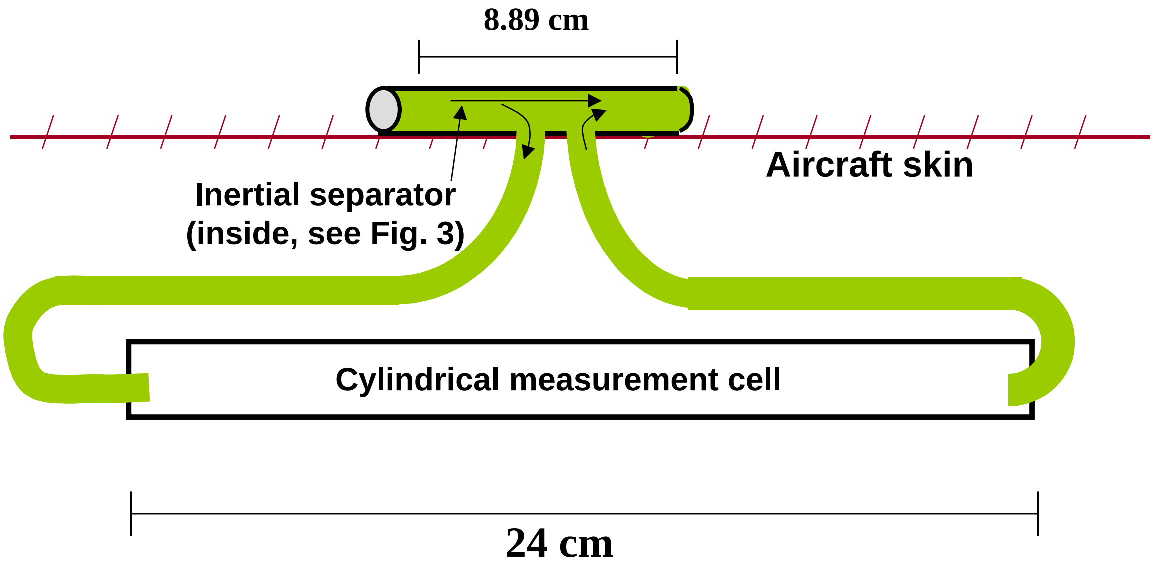


Figure 2. Cross section of complete sampler

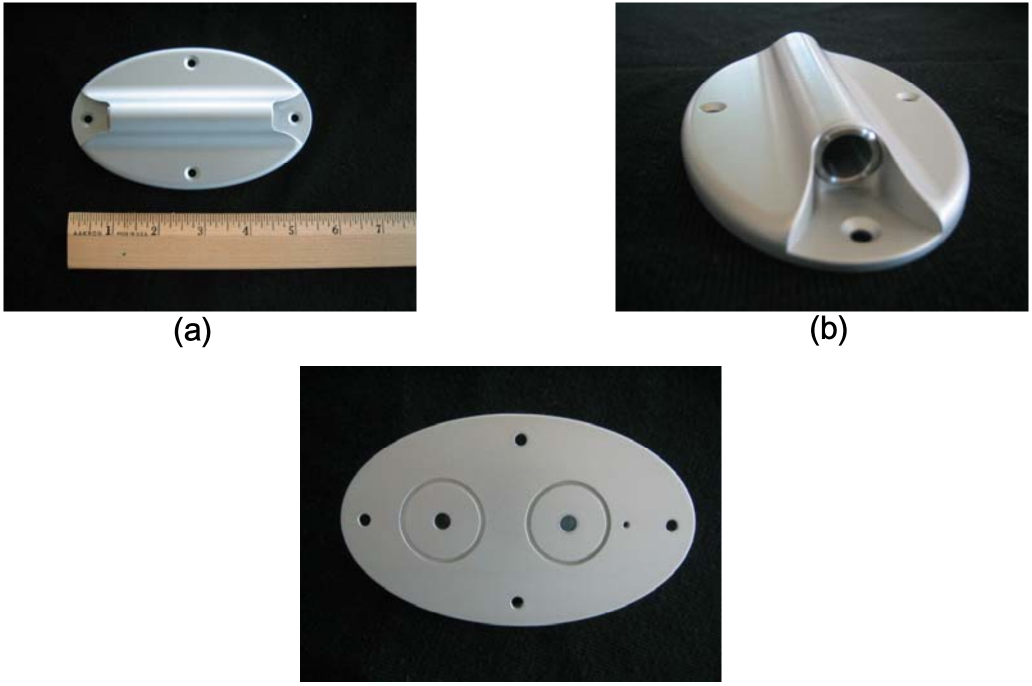
The measurement cell is located just inside the aircraft. Note that the same performance can be obtained with the 24 cm path length achieved with a mirror located at the end of a 12 cm path. This is the actual configuration for the WVSS-II. The electronics box and measurement cell are combined into a single unit with a single part number.

The same physical hardware indicated in Figure 2 can be utilized for the measurement of other atmospheric trace gases. The diode laser could be replaced by a quantum cascade (QC) laser. These lasers are just beginning to become available (see Capasso, et al, 2002) – though current prices are relatively high. These QC lasers are single mode lasers in the mid-IR range. A summary of such lasers and the gases they can detect is shown as on the website http://www.atmoschem.jpl.nasa.gov/PDF_Papers/NearMid_IR_Webster.pdf. The air sampler described in the next section is optimized to obtain maximum sensitivity from the diode lasers and QC laser measurement systems on commercial aircraft and on UAVs. The system for UAVs has all components scaled down in size from those described here in this document.

2.2 UCAR Air Sampler

The **mixing ratios** of measured quantities like water vapor and atmospheric trace gases are **conserved properties** whether they are measured in static conditions, in fully dynamic conditions (including the Mach number effect of the fast moving aircraft), or in conditions between these two extremes. The UCAR air sampler has been designed to take advantage of this fact, thus eliminating the negative features of past probes on jet aircraft, and further designed to optimize conditions in the measurement cell for diode and QC lasers.

Figure 3 shows pictures of the UCAR air sampler from different perspectives. It is only 9 cm long and flush mounted with the aircraft skin. The fact that the aircraft skin may heat the air above ambient is of no concern to our measurement as the mixing ratio is conserved. The temperature and pressure within the measurement cell are between ambient (static) and dynamic values. These values are obtained within the measurement cell with accurate protected sensors located near the laser path so that the absorption cross section in Eq. (1) is accurate.



(a) (b)

(c)

Figure 3. UCAR air sampler (a) top view, (b) side view, and (c) bottom view.

The flush mounted air sampler thus saves on fuel costs since there is virtually no drag (compared to the 2.5 lbs of drag associated with a TAT probe). Also since the UCAR air sampler does not have to be heated (not an icing issue just as the similarly shaped GPS antenna is not an icing concern) this saves energy – and far more important, eliminates the major failure mode of the TAT probe: its heater.

The diode laser used for water vapor measurements on the WVSS-II operates at 1.37 µm. This wavelength is not **absorbed** by ice crystals or aerosols, however, a very large number of such ice crystals or aerosols could **scatter** the laser light and reduce the sensitivity of the diode laser at the cold dry regions of the upper troposphere. **Thus, a second goal of the sampler design is to remove ice crystals and aerosols that could hinder the sensitivity of the measurements in the cold, dry upper troposphere.**

The NCAR air sampler is aerodynamically designed to remove particles from the air flow. Since these particles have a density which ranges from a factor of 10 [(new snow) to 100 (snow crystals) to 1000 (aerosols)] more dense than the gaseous water vapor, they can be inertially separated by accelerating the flow over the aperture in the air sampler leading to the measurement cell and forcing the majority of such particles out of the rear of the external portion of the air sampler. Simulations suggest that the degree of efficiency of this process ranges from 81 to 95% of the unwanted particles being removed.

A final goal of the UCAR air sampler design is to slow the flow to the measurement cell inside the aircraft. This is achieved by an obstacle in the air sampler and by the smaller diameter hose feeding air into the larger diameter measurement cell as seen in Figure 2. The amount of flow required to achieve a minimum exchange of air for sampling purposes is quite small. The response time of the diode laser is fast (high frequency spectra are averaged to produce a final answer every two seconds). Since one might require a minimum of two complete flushes of air in the sample cell per unique measurement, that would demand a flow of 12 cm s^{-1} to flush the measurement cell (12 cm long) every second.

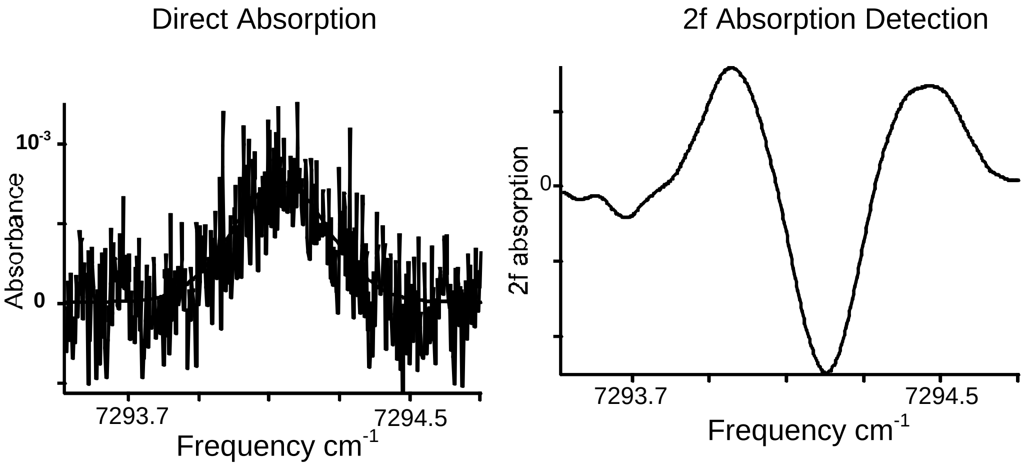
The flow could be much stronger for independent measurements but there is a reason to hold the flow to less than 10 ms^{-1}. The temperature structure around the laser source/receiver head (both located together on the same plane) should be relatively uniform. Computational fluid dynamic methods have been used to show that the combination of the obstacle height in the air sampler and the ratio of the hose diameter lead to a flow velocity of 3-6 ms^{-1} in the measurement cell.

2.3 System Accuracy, Precision, and Testing

All aspects of the processing cannot be revealed in this summary document. Special efforts can achieve an accuracy of ± 5 % of the signal at all levels of the atmosphere typically flown by commercial aircraft. One method of improving accuracy and precision (sensitivity) is to use 2nd order harmonic detection. From Equation (1) the absorbance (α) is given by:

$$\alpha = \sigma n \ell = -\ln\left({}^{I}\!/\!{}_{I_0} \right) = \ln\left({}^{I_0}\!/\!{}_{I} \right)$$

The measured laser power (I) varies as a constant-period sawtooth current ramp is applied to the laser to scan the output wavelength over the desired spectral interval (typically 1-3 cm^{-1}). I_0 is the measured laser power at the spectral line center in the absence of absorption. A small-amplitude sinusoidal waveform at frequency f is added to the ramp, and the measured (detected) signal (I) is demodulated at $2f$ to produce a second harmonic spectrum. A comparison of direct absorption detection and $2f$ absorption detection is shown in Figure 4 to illustrate the sensitivity improvement obtained using the $2f$ technique. One sees that the signal to noise ratio (S/N) improves by a factor of 50 – thus a similar improvement in sensitivity. Another aspect of the processing is that the $2f$ signal amplitude is ratioed to the measured laser power at every measurement to ensure that changes in laser power, laser drift, and mirror contamination do not affect the water vapor mixing ratio.



Absorbance = 7.5 x 10^{-4}
S/N = 2

Absorbance = 7.5 x 10^{-4}
S/N = 100+

Figure 4. Direct and 2*f* Absorption Detection.

Many laboratory tests have been conducted at SpectraSensors with their calibration and test station equipment. Figure 5 shows a typical run where the moisture is constant and the pressure is varied. The minimum sensitivity of the WVSS-II is 3 ppmV. This lab run for dry conditions (dew point essentially constant between –25.3˚ C to –25.8˚ C) raises pressure from 160 hPa to 994 hPa in steps about 4 min. apart. The chilled mirror dew point (frost point) values are considered truth (chilled mirror calibrated to a National Standard). Pressure is accurately measured at both sensors (needed to convert dew points to mixing ratio). The spike in the WVSS-II data (very low values at the beginning of each "pressure change segment") is real. At the pressure change, for an instant, the flow of the water is zero. One can see how fast the WVSS-II recovers compared to the usual oscillation seen in chilled mirrors. Also note that the final values agree at all pressure levels.

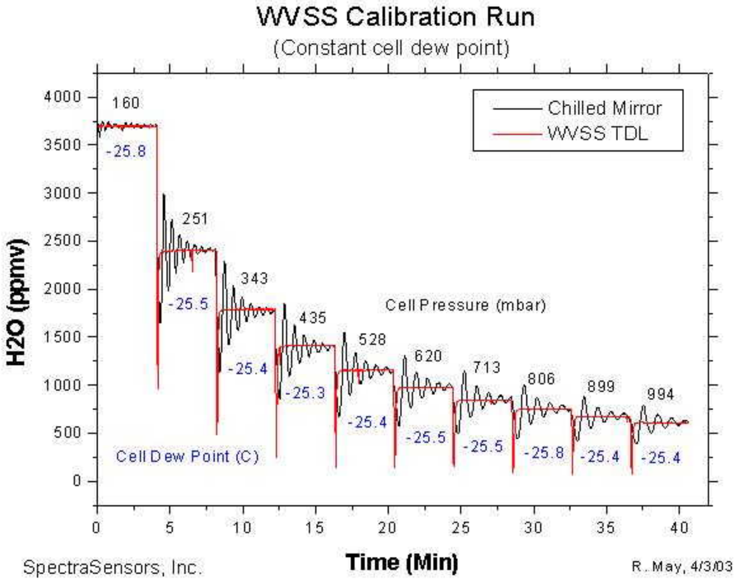


Figure 5. Calibration run.

The schedule in the WVSS-II development of a fully commercial product for commercial and military aircraft coincided with the opportunity to fly the WVSS-II on the National Oceanic and Atmospheric Administration (NOAA) P-3 research aircraft for Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX). The only location available on the aircraft was further back on the fuselage (next to the propeller on the right hand side) in a less than optimal location compared to the chilled mirror in a forward portion on the fuselage. The location is shown in Figure 6 where the normally metallic air sampler of Figure 1 is seen in red mounted on a blue window-plate.

A typical flight test result is shown in Figure 7 where data from the WVSS-II are compared with the standard chilled mirror on the NOAA P-3. The data match up extremely well in amplitude and phase (except where in rapid changes the chilled mirror tends to “overshoot” — a common problem with chilled mirrors in such conditions). Figure 7 shows time in seconds on the lower horizontal scale; the measured static pressure (blue line – reference the right scale), which indicates constant flight level between 10,000 and 20,000 seconds followed by a series of up and down maneuvers; the water vapor, measured as mixing ratio in parts per million by volume (ppmV) on the left vertical scale; and a very close match between WVSS-II (black) and the NOAA P-3 standard chilled mirror (red).

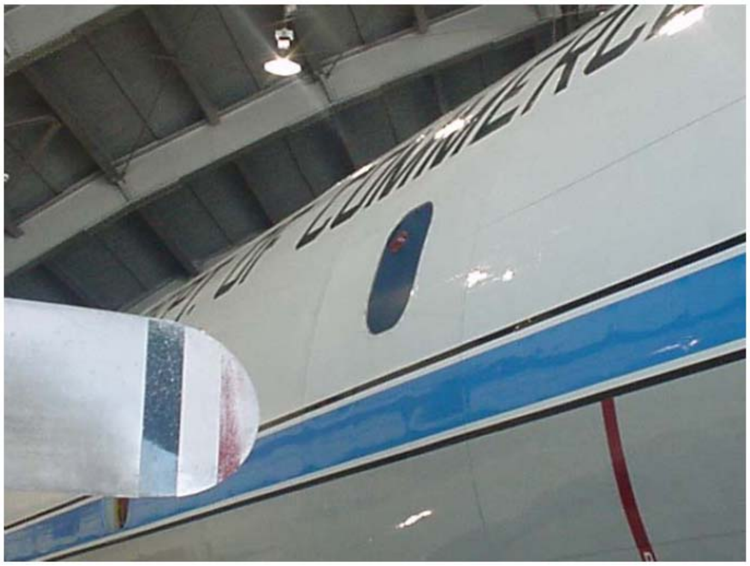


Figure 6. WVSS-II air sampler (red) mounted on blue window plate.

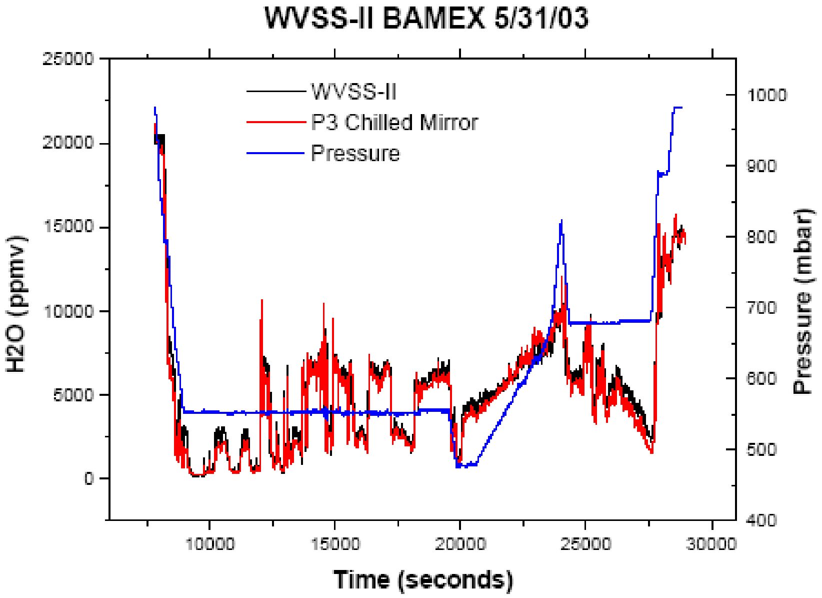


Figure 7. Flight test

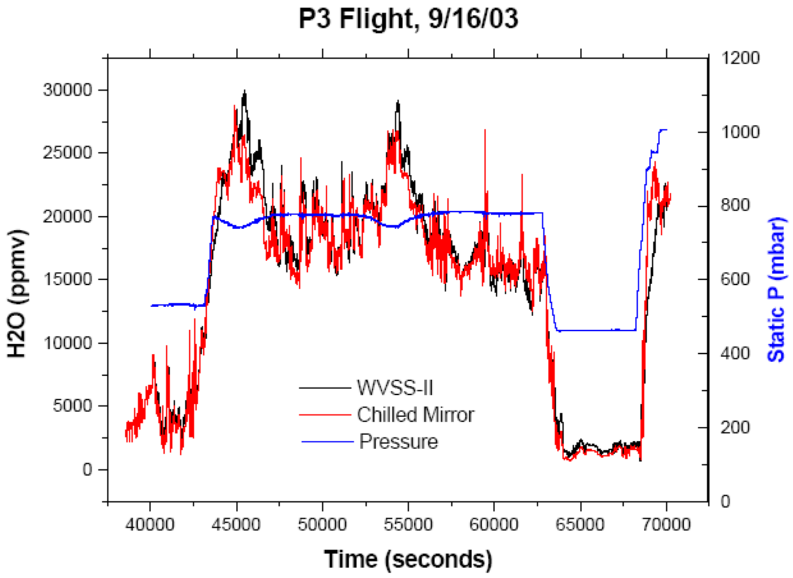


Figure 8. Data comparison of Isabel flight.

After BAMEX, the WVSS-II was returned to SpectraSensors. Lab tests revealed that the calibration was still exactly the same as the previous calibration run. The WVSS-II was subsequently sent back to NOAA and installed on a second P-3. The second aircraft subsequently flew in hurricane Isabel and Figure 8 shows further comparative results of the two sensors in an extremely wet environment. Note the very wet conditions of nearly 30,000 ppmV at 800 mb in the flight of Figure 8. There should be no change in accuracy due to the laser diode unless the laser power gradually falls below 5% of its original value. An error flag (part of the data transmitted in real-time during operation on commercial aircraft) indicates when the laser power falls below 10% of its original value. This is one of the “smart sensor” attributes of the WVSS-II, which provides an early warning housekeeping function.

3. Operational Aspects of the WVSS-II

3.1 Aircraft and Air Carrier Interfaces

The WVSS-II requires very little power to operate, and uses the aircraft's standard 28-volt power supply. The maximum power consumption is dominated by the 13-watt capacity thermoelectric cooler (TEC) element used to stabilize the laser temperature. The remaining control electronics require only one watt. Thus, the maximum current required is a mere (14 watts/ 28 volts) = 0.5 amps.

The air sampler can be mounted in a wide variety of places (generally toward the forward portion of the aircraft). The external (to the aircraft skin) air sampler is connected to a doubler (filler) plate beneath the skin. The quick-disconnect pressure hoses attach to the doubler plate and to the measurement cell (located within the Systems Electronics Box (SEB)) – which houses both the measurement cell and the system's electrical components. The entire weight of the air sampler, hoses, SEB and mounting brackets is approximately 6.5 lbs.

The installation and removal of the SEB is quite simple. It is attached to a floor beam adjacent to the air sampler location via two bracket assemblies as shown in Figure 9. Inlet and outlet hoses for air flow are mounted permanently to the floor beam and can stay in place with or without an SEB present. The SEB is held to the bracket assembly via six mounting bolts that screw into nut plates riveted internally to the SEB. Installation involves placement of the SEB between the mounting brackets and insertion of the six mounting bolts, followed by connection of the inlet and outlet hoses. Removal is the reverse of this process.

We expect no maintenance requirements for the WVSS-II except during a standard C-check. Such C-checks vary with aircraft type but generally occur between a 2.0 – 2.5 year cycle. During the C-check, the SEB will be removed and replaced with a spare. This should take no more than 30-60 minutes. The removed SEB is sent back to SpectraSensors (or an agreed-upon avionics supplier) where the system is cleaned and sensors replaced as necessary.

3.2 Communications Interfaces for Data Users

The four-character set of WVSS-II data is already defined in the ascent, descent, and enroute phases of flight in ARINC-620, Version IV – the AEEC sanctioned format for real-time Aircraft Communications and Reporting System (ACARS) data. Major data service providers can process this ACARS data in virtually all parts of the world. The required avionics on the aircraft is a Digital Flight Data Acquisition Unit (DFDAU), or a similar variant, with an additional (separate or included) ACARS box. Other communications systems are possible. Atmospheric water vapor mixing ratio varies over four orders of magnitude.

ARINC 620 has a four-character water vapor information field (NNNQ) where the first three characters are integers (NNN) with the following meaning:

$$NNN = N_1N_2N_3 = N_1 \bullet N_2 \text{ x } 10^{-N3} \qquad \text{(kilograms/kilograms)}$$

For example:

$123 = 1.2 \times 10^{-3}$ $345 = 3.4 \times 10^{-5}$
$404 = 4.0 \times 10^{-4}$ $000 = 0.0 \times 10^{-0} = 0.0$

The value Q is a Quality Control Character and its value has the meaning defined in the Table below.

Q	System State	Software Logic
0	Normal operation	Air/Ground = Air
1	Calculated RH > 100%	RH > 100%
2	Input laser power low	Laser < 10% of initial power
3	Measurement cell temp. out of range	Proprietary information
4	Measurement cell pressure out of range	Proprietary information
5	Spectral line shift, missing	Proprietary information
6	No laser output	Proprietary information
7	Not defined	
8	Numeric error	e.g., divide by zero
9	No WVSS installed	No WVSS installed

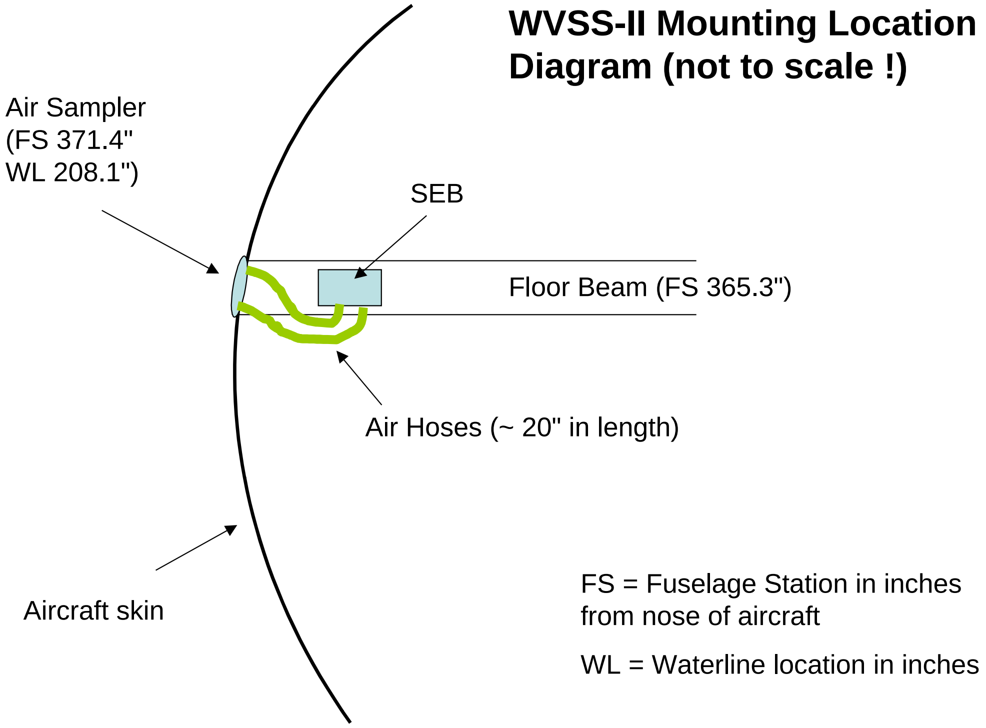


Figure 9. Cartoon of WVSS-II mounting (looking towards the nose of the aircraft).

4. Benefits of Improved Water Vapor Information for Air Carriers and Society

4.1 Nowcasting and Very Short Term Production

A dominant attribute of water vapor is its role as a volatile fuel for dynamic change in the atmosphere (not unlike volatile jet fuel for an aircraft). It requires 2500 Joules of solar energy to evaporate a single gram of water from the ocean (the conversion of liquid water to vapor form). When air is lifted and cooled sufficiently, this 2500 Joules/gram is released as heat into the atmosphere when the vapor condenses back to water or ice. A second attribute of water vapor is that wet air is lighter than dry air (just as warm air is lighter than cold air). This implies that water vapor substantially contributes to the stability or instability of the atmosphere.

A list of atmospheric phenomena that affect aviation in the very short-term from nowcasting (situation awareness) to predictions at least an hour in advance include: (i) ceiling and visibility; (ii) convection of various degrees of severity (microbursts, convective turbulence, thunderstorms, and severe thunderstorms with hail); (iii) wake vortices; (iv) precipitation (timing, type, amount); and (v) snow/ice storms (timing, intensity). All of the above phenomena depend upon the stability or instability of the atmosphere and/or the amount of water vapor present. These important influences of water vapor are mostly missing in aviation weather support today because water vapor is simply not sufficiently measured on the short time scales required nor with the proper vertical resolution from satellite data. The addition of the water vapor measurement from the WVSS-II will aid aviation **safety, efficiency and capacity.**

The high resolution ascent/descent data provides aviation support to those researchers engaged in improving aviation **safety**. These data will lead to better safety performance and smaller insurance premiums for aviation in general. The value to various national weather services is the greater mesoscale space/time coverage provided by the commercial aircraft with the WVSS-II providing the three fields of information important for the short-term weather forecasts for society.

A more **efficient** air traffic system is also in air carrier's interest for similar economic reasons as for safety listed above. A number of new aviation weather products will improve both safety and efficiency when more water vapor data provides better forecasts (e.g. of convective areas) and this is fed back to air traffic control systems. This efficiency in air travel translates to more demand for air travel over time and an improved financial bottom line for air carriers. Air travel is returning and is expected to grow to the extent that **capacity** issues will reappear. The ability to have more approaches and departures, closer en route separation patterns, and other measures that might be used to increase capacity are, to a large degree, dependent upon our greater ability to detect and understand impacts of aviation weather.

4.2 Extended Range Weather Prediction

Improved weather prediction beyond an hour is important for aviation. Concerns out to 8-10 hours include accuracy in IFR/VFR conditions and storm locations **as predicted** (dictating alternative landing sites and fuel on board). Applications include weather-based decisions by air traffic control officials in summertime convection conditions, which can lead to major delays at airports (especially at key hubs). Improvements in weather prediction for all countries occur when the initial conditions of the atmosphere are more frequently and accurately measured.

Radiosondes are too few and far between. Satellite data have large error bars in general, vertical resolution, which is too coarse, and water vapor information, which is quite poor **quantitatively**. Not only are the ascent/descent data valuable, but also the en route data, filling gaps in observational coverage and helping to calibrate the satellite data.

4.3 Air Quality Applications

The growing world population, emerging economies of developing nations and complex chemical manufacturing processes have given rise to a worldwide need for better air quality measurements. Countries are considering three-dimensional measurement programs to observe, model, and predict a variety of chemical species. Such an effort would require a variety of ground and satellite measurement techniques. An ideal synergistic platform for making vertical profile measurements is the commercial aircraft. As mentioned above, the use of the new QC lasers with the UCAR air sampler could provide vertical measurements for a large variety of species during ascent and descent. Such data would be sent in real-time, expenses paid by the government agency desiring the data, and the program would represent a win-win situation for all concerned. Such an arrangement would place the airline industry in a very favorable role as a major supporter in the stewardship of the Earth's atmosphere.

4.4 Reduced Uncertainty in Global Climate Change

The Intergovernmental Panel on Climate Change (IPCC) has indicated that the perceived warming of the surface air temperature over the planet is caused by mankind and the continued increase in greenhouse gases will raise the warming of the planet to the point of melting the Antarctic ice cap, raising sea level and flooding many coastal cities. Some have questioned the intensity and timing of the computer models responsible for these projections.

The IPCC has recently written a report that is the first to single out a specific industry and has targeted the aviation community in a document called "Aviation and the Global Atmosphere". There are many uncertainties concerning the global climate warming issue. One of the major uncertainties in the global warming issue is atmospheric water vapor. The climate computer models have temperature increasing 2-3 % (in degrees Kelvin) with a doubling of CO_2 and a corresponding increase in the total water vapor content of the atmosphere from 10-20%. It is this increase in water vapor loading that is most effective in the model's final temperatures (water vapor is 10 times more effective as a greenhouse gas than is CO_2). **We have seen one degree of warming in the last 100 years but have yet to see convincing evidence of a water vapor increase!** The radiosondes show a very slight water vapor increase (very uncertain due to changing manufacturing practices and software changes that bias measurements) and the satellites show a very slight decrease in water vapor (a short record with its own set of uncertainties). If climate models are in error and global water vapor loading only increases at the same 2-3 % level this will not lead to enough heating to melt the ice cap and raise sea level. Climate models can be improved (and the uncertainty reduced) with substantially more water vapor information from a fleet of commercial aircraft traveling the globe. These data can provide two orders of magnitude more in-situ data per day and provide accurate data to calibrate current and future satellite data over the planet.

Appendix

The purpose of this appendix is to provide a cross-section of applications of the diode laser technology. This summary is not meant to be all-inclusive and apologies to those whose important contributions are not listed. The listed applications are in chronological order.

Early examples of diode laser use in the 1980s are provided in the published scientific literature (cf. Menzies et al, 1983, and Webster and May, 1987). Often the literature has these single mode diode lasers described as "tunable" diode lasers. These are still single frequency lasers, but the frequency of interest can be scanned with a constant-period sawtooth current ramp applied to the laser, which results in a very **slight** frequency change – a frequency change just over the desired spectral interval (typically 1-3 cm^{-1}).

An example of one of several commercial firms to use diode lasers is Norsk Electro Optikk (NEO) in Norway. Established in 1985, this company used diode lasers as part of gas monitoring instruments for industrial applications. This company is still in business selling those products – a testimony that they perform quite well. Information on this company can be found on the web at http://www.neo.no.

A landmark paper that established the "open path" diode laser system as the "standard" for all research water vapor measurement systems is that of May, 1998, which describes a system on the NASA ER-2 aircraft. This system has become the standard of comparison for other research observing systems that measure water vapor on research aircraft. One example is the Harvard Lymon-α system (cf. Hinsta, 2000). See Figure A1 where the right side of the Figure appears in the reference of Hinsta (2000).

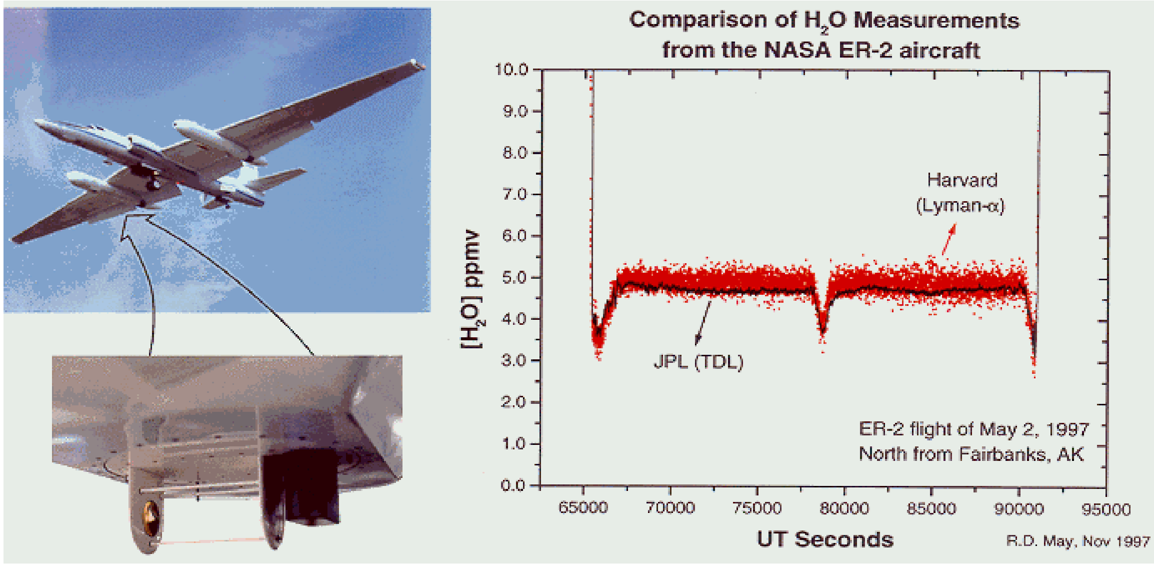


Figure A1. NASA ER-2 system.

An example of the diode laser inside a total air temperature (TAT) probe as used on commercial aircraft was demonstrated in August of 2000. This was the smallest TAT probe made by the B.F. Goodrich corporation for commercial aircraft and was mounted on the National Center for

Atmospheric Research (NCAR) C-130 research aircraft. This early "prototype WVSS-II" was mounted on the wing pod under the C-130 with the "open path" diode laser system mounted next to it. A picture of the systems on the wing pod can be found in Fleming, et al (2003). Figure A2 shows results of these two systems compared to the NCAR standard chilled mirror for this aircraft. Except where the chilled mirror "overshoots" in rapidly changing conditions (a known common occurrence with chilled mirrors) the data from all three systems agree with each other. The "prototype" WVSS-II agrees with the open path system –their results are virtually identical for the entire flight path. This open path system has become standard equipment for this aircraft.

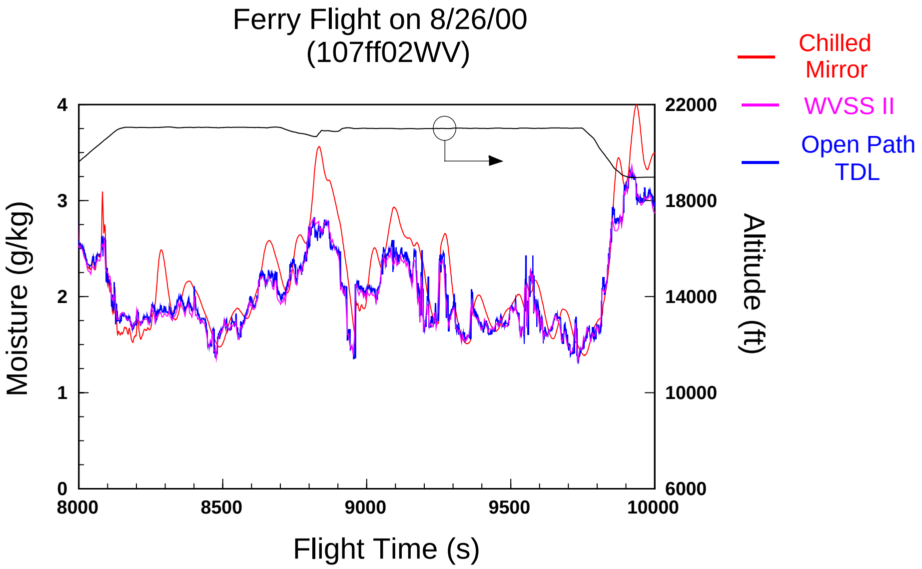


Figure A2. NCAR C-130 Flight Test Result.

SpectraSensors, located in San Dimas, CA, has been developing water vapor measuring systems for the natural gas industry since April 1999. The diode laser used in this system is **identical in material and fabrication** as those lasers used in the telecommunication industry to reliably carry the world's communication signals. **These are also the same diode lasers used in the WVSS-II!** These lasers are "Telcordia (formerly Bellcor) certified (GR-468-CORE)" which is an industry standard similar to "FAA certification." Their lifetime is 20 years. Nearly 200 of these "Laserchek" units for the natural gas industry are in use around the world in exotic places. Thus far, there have been no failures or repairs required for these systems. This business is just beginning to grow (during the last two months of 2003 the units shipped per month jumped from 5 to 14 per month). Figures A3 and A4 show the Laserchek system in the field.

With the decision to forego the TAT probe with the diode laser inside, the SpectraSensors laser system was combined with the UCAR air sampler and this now is the WVSS-II, which is the established commercial product as described earlier in this document. The laboratory and flight test results of this system are shown in Section 2.

Figure A3. Laserchek system.

Figure A4. Laserchek in field.

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