Summary of Atmospheric Water Vapor Information from Sensors on Commercial Aircraft: Measuring Relative Humidity Versus Mixing Ratio

Report

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1. Introduction

An evaluation has been made of the measurement of relative humidity (RH) and the measurement of atmospheric water vapor mixing ratios on commercial aircraft. The water vapor sensing system (WVSS-I) using a thin film capacitor for RH measurements has been rejected in favor of the WVSS-II, which uses a SpectraSensors diode laser system to measure the mixing ratio. There were three very serious reasons and two other concerns that led to the WVSS-I being discarded by both the Federal Aviation Administration's (FAA) Aviation Weather Research Program and the National Oceanic and Atmospheric Administration's (NOAA) Office of Global Programs. These reasons and concerns are systematically discussed below and based upon exact mathematic formulae, statistical analysis, carefully evaluated laboratory tests, and several years of operational evaluation.

2. WVSS-I and RH Measurements Results

A competitive request for proposals (RFP) was released by the Dept. of Commerce (NOAA) to industry on September 27, 1994 (nearly 10 years ago). The competitive evaluation was conducted by a Source Evaluation Board (SEB) composed of members from the FAA, the National Science Foundation (NSF), NOAA/National Weather Service (NWS), and NOAA/Office of Atmospheric Research. Prior to this RFP release an FAA funded study was conducted by NCAR on possible technologies – revealing that diode lasers (measuring the atmospheric water vapor mixing ratio) would be the best technology for a fast moving jet aircraft and that the measurement of RH (by any technology) would have an inescapable flaw on such aircraft (described below). However, only three proposals were received (none proposed a diode laser, which was too expensive at that time): one for a chilled mirror (accurate, but impractical for commercial aircraft), and two using the Vaisala thin film capacitor for the measurement of RH.

The winning contractor was Lockheed Martin Corporation (LMC), which used the Vaisala thin film capacitor for measuring RH (a more robust version than used on the Vaisala radiosondes). Subcontractors to LMC were the B.F. Goodrich Corporation for the manufacture of the WVSS-I (using their TAT probe as the air sampler with the Vaisala sensor added), the avionics company Allied Signal (for the software conversion of the then newly created ARINC 620 high resolution ascent/descent format for wind, temperature, and water vapor information profiles (the measured static RH values were converted to mixing ratio), and United Parcel Service (UPS) as the air carrier to both certify and fly the WVSS-I. Test results were evaluated by experts from NOAA, UCAR, Univ. of Wisconsin, and UPS. This document is only a summary; the details are found in the reference Fleming, et al (2002) and other references cited later.

2.1 Mach Number Effect

The first major flaw for any RH measurement on a jet or turboprop aircraft is the "Mach number effect". This was first described by Hills and Fleming (1994) and later addressed further in Fleming, et al (2002). Rather than force the reader to go to those references, one can repeat the relevant equations here and quickly summarize the result. The **total** air temperature (T_T) measured on an aircraft equals the **static** temperature (T_S) or ambient temperature plus the dynamic effects of the moving aircraft. The total temperature is given by

$$T_T = T_S\,(1 + 0.2\,M^2) \quad (1)$$

where T is always in degrees Kelvin and where M is Mach number (speed of aircraft relative to the speed of sound at M = 1). The total pressure (P_T) is similarity related to static pressure (P_S) by:

$$P_T = P_S\,(1 + 0.2\,M^2)^{3.5} \quad (2)$$

The most common form of relating the amount of moisture in the air is via the RH. This is defined (with respect to water, per the World Meteorological Organization) as:

$$RH = (e/e_s)100 \quad (3)$$

where RH is a percent, e is the atmospheric vapor pressure (Pascals), e_s is the saturation vapor pressure with respect to water (Pascals); e_s is defined as saturation vapor pressure with respect to water by Fan and Whiting (1987) as:

$$e_s = 10^{[10.286T - 2148.909)/(T - 35.85)]} \quad (4)$$

Another form of measurement of the water vapor content in the atmosphere (used by most meteorological prediction models) is the mixing ratio (mass of water to mass of dry air).

$$r = 0.62197e\,/\,(P - e) \quad (5)$$

where e is vapor pressure and P is pressure. Since the mixing ratio is conserved whether outside the aircraft (static environment) or within the aircraft's measurement probe (virtually identical to the total dynamic environment), the water vapor mass is unchanged and the following relation holds:

$$\frac{e_{static}}{e_{probe}} = \frac{P_{static}}{P_{probe}} \quad (6)$$

where the subscript static refers to ambient conditions and the subscript probe refers to values in the probe. It can be shown that combining Eq. (6) with the definition of RH, Eq. (3), leads to

$$\mathrm{RH}_{\mathrm{static}} = \mathrm{RH}_{\mathrm{probe}}\left[\frac{\mathrm{e_s, probe}}{\mathrm{e_s, static}}\right]\left[\frac{\mathrm{P_{static}}}{\mathrm{P_{probe}}}\right] \quad (7)$$

The impact of Eq. (7) is primarily felt at "flight level" where the Mach number is relatively high and it has a small impact on "ascent" and "descent" where Mach numbers are much lower. Figure 1 is a plot of Eq. (7) where the ratio of RH_{static} to RH_{probe} is shown as a function of Mach number and temperature. One can see from the figure that for high Mach numbers and very cold temperatures, this ratio becomes substantial. This Mach number effect is due to the highly nonlinear nature of Eq. (4) and the effects of dynamic heating through Eqs. (1) and (2).

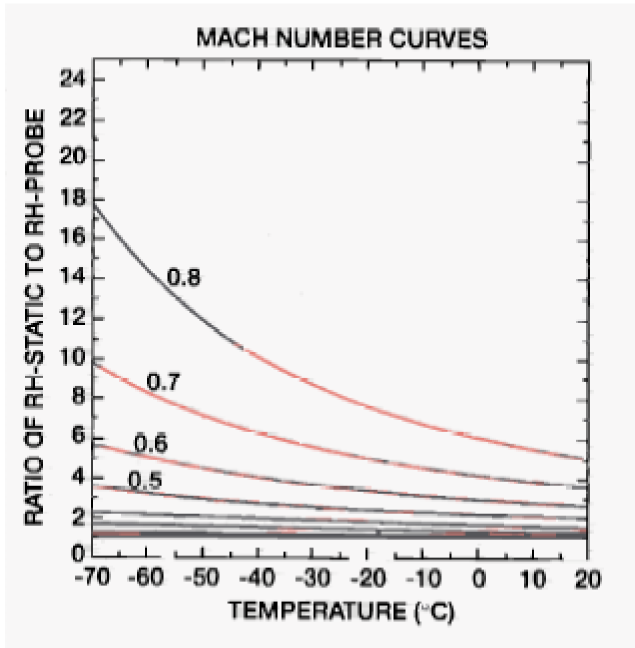


Figure 1. Ratio of RH_{static} to RH_{probe} as a function of temperature and Mach number. Mach number curves from 0.8 to 0.5 are labeled, the lower curves approach the value of 1.

The above curve is not to be confused with actual accuracy or uncertainty. This ratio is an **amplifier** of the error uncertainty of the actual measurement of RH in the probe on the aircraft (RH_{probe}) – see Equation (7). The accuracy of (RH_{probe}) will depend upon the fundamental accuracy of the sensor (Vaisala's thin film capacitor in this case) and the effect of the uncertainty of the temperature measurement (also needed in the definition of RH through e_s). This accuracy is covered in Appendix 3 of Fleming, et al (2002). This RH_{probe} error as a percent of signal (ΔRH/RH) is shown to be 4 – 6 % as a function of temperatures and assumptions of temperature accuracy.

In the following analysis we consider a jet aircraft flying at Mach = 0.8 and a turboprop aircraft flying at 315 mph (141 m/s) with a ceiling of 25,000 feet. Using the standard atmosphere for temperature at this flight level (T = 238.6 K) the speed of sound at this flight level would be 310 m/s. The turboprop would fly at Mach 0.45 (a range of M = 0.4 to M = 0.5 is probably typical at usual flight levels). Optimistically, consider an aircraft temperature sensor that can measure temperature to ± 0.4 K (table 1 in Appendix 3 of Fleming, et al, 2002 used ΔT = 0.59 K to 0.88 K and T = 0º C or T = 273.15 K for the (ΔR/RH) values of 4 – 6 % stated above). This lower ΔT would give the accuracy of (RH_{probe}) as (ΔRH/RH) = 3 % for the above conditions for the turboprop aircraft. Note that radiosonde errors are considered to be ± 5 % in the middle troposphere where turboprops fly.

Figure 2 shows the error as a percent of signal for typical jet aircraft (top curve) and typical turboprop aircraft (lower curve). The errors are shown over the range of temperature from –70 to 0º C to cover turboprop aircraft that fly as low as 18,000 feet (where standard atmosphere temperatures would be about –20º C, but the dynamic heating from Equation (1) would raise the temperature on the probe to about 0º C. **These errors for the turboprop aircraft are all above 10 %. This Mach number effect is why RH should not be measured on a moving aircraft, however, as stated in the references, the WVSS-I can compete with radiosondes on**

ascent and descent where the Mach number effect is small and where radiosondes have their own set of problems. One must emphasize that this Mach effect applies to RH measurements only (using thin film capacitors or hygristors) and does not occur for mixing ratio measurements with diode lasers nor for dew point measurements with chilled mirrors.

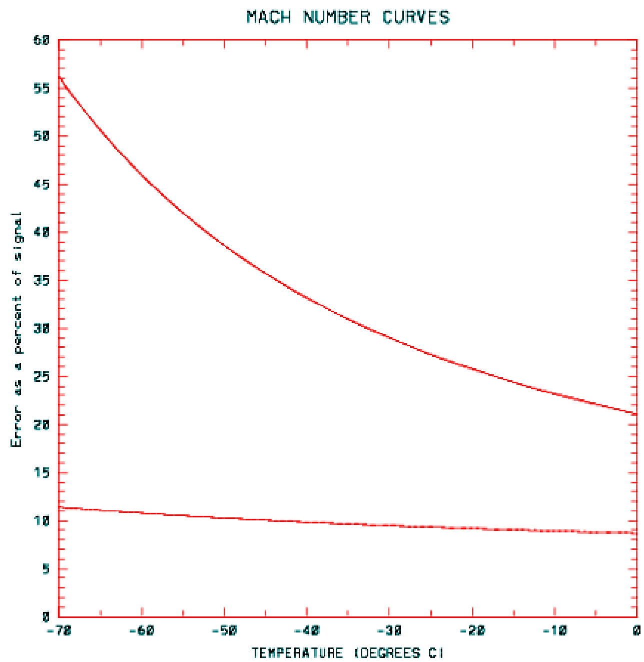


Figure 2: Error as a percent of signal for ambient RH. The random error of the RH sensor in the aircraft probe is assumed to be ± 3 % (see text). The upper curve is for jet aircraft flying at M = 0.8. The lower curve is for a typical turboprop flying M = 0.45.

The loss of accurate flight level moisture information from regions of the atmosphere flown by both jet and turboprop aircraft has a negative impact on many aspects of the NWS mission. Only four examples are provided below.

(1) Maximum temperature forecasts at the Earth's surface are apparently biased warm because of an inability to accurately predict thin cirrus clouds – water vapor information at these upper tropospheric levels are notoriously bad due to both radiosondes and satellite inaccuracies at these levels.

(2) Improved regional and global analysis through 4DDA methods can be dramatically improved with **accurate** in-situ data from commercial aircraft combined with the satellite water vapor images, which are accurate in terms of the horizontal gradients of information – but which lack absolute accuracy in magnitude. Kalman filter techniques can combine these data sets to produce a whole greater than the sum of the parts.

(3) Extended range weather prediction (beyond a few days) requires accurate upper level moisture information as shown by the European Center for Medium-Range Weather Forecasts (ECMWF).

(4) The timing and intensity of global warming has serious uncertainties due to upper level cloudiness and the lack of water vapor information – thus, accurate water vapor information is needed in its fundamental role of cloud formation and is required for assessing whether the atmosphere's water vapor loading is increasing as climate models suggest.

2.2 Calibration Issues

A second major concern of the thin film capacitors used to measure RH is that they are difficult to calibrate at the high end of the RH range (0 – 100 %) and have difficulty holding precise calibration at any range over even short time intervals – just like radiosondes that measure RH. In our first 6 "production" WVSS-I units produced and flown on the UPS B-757 aircraft we had one unit that tested with a moderately dry bias and one unit that tested with a moderately wet bias (see Fleming et al, 2002).

A one-year delay occurred in the WVSS-I evaluation as UPS switched avionics companies (Allied Signal to Teledyne). Thus the original 6 units were "repaired" (cleaned, sensors replaced and recalibrated) and 24 others were built and installed for a total of 30 units. In the second set of 30 units, 10 % (3 units) were found to have a severe wet bias that either formed early on or was an initial improper calibration. The calibration for the WVSS-I was performed by the B.F. Goodrich Corporation and was only conducted over the range of 0 – 70 % RH. This was a matter of convenience and practicality. It is difficult to calibrate these sensors at high RH values. For example, NIST has evaluated Vaisala thin film capacitors only up to 90 % RH. (The difficulty apparently has to do with both achieving and holding saturated conditions in a laboratory environment for a sufficiently long time period to get good, accurate statistics.) UPS' meteorological staff were very dissatisfied with the calibration issue – while some aircraft tail numbers could be trusted and their data used in a valuable way for operations, others could not be trusted and it took time to identify these aircraft tail numbers.

2.3 Loss of Thin Film Measurement Sensitivity Over Time

A third major concern of using thin film capacitors measuring RH is loss of sensitivity over time – leading to a dry bias. This had been seen in Vaisala radiosondes when outgasing from a protective cover had led to sensitivity losses while the sondes were stored on the shelf. This has been predominantly (but not entirely) fixed by a change in storage methods. However, the mere interaction of ambient air over time will lead to a loss of thin film sensitivity over time and a resulting dry bias. This dry-bias is exacerbated by the trace chemicals and aerosols that come in contact with the capacitors while on a commercial aircraft (note that two sensors on the aircraft will both age over time and one cannot be considered a backup for the other unless one is kept in a vacuum state until needed).

Early tests on this condition were conducted by NCAR – using accelerated flow meters on the roof of NCAR operating 24 x 7 to simulate long life time (3 month operating conditions) on an aircraft (Hills and Fleming, 1994). This same loss of sensitivity and resulting dry bias was seen for several Vaisala thin film sensors with various filters used on each.

A method of checking the results for the 30 UPS WVSS-I aircraft was devised to check for this dry bias over time. This was a monthly check of whether the unit recorded RH of 95 – 100 % **at least once** during that month at various flight levels ranging from 10,000 to 40,000 feet. All aircraft will penetrate clouds (including cirrus at upper levels) at least once during their many hours of flight over a period of a month. This test would be failed first by the WVSS-I units at the upper levels of the atmosphere where the thin film capacitors are relatively less sensitive anyway due to cold temperatures. As the units began to lose sensitivity, this failure would progress to lower and lower levels.

When the test failed over consecutive months and reached 30,000 feet, the unit was considered to be “failed” as the dry bias had become too serious for properly assessing accuracy at the lower levels. This test then gave a “lifetime” to the WVSS-I units, which was recorded for each aircraft and for each WVSS-I unit as it was “repaired” (given a new sensor and recalibrated). Thus, there were 56 lifetimes and the average was approximately six months. This six-month lifetime (as depicted by this simple gross error check) indicates nothing about the dry bias problems that may have affected average conditions over the 3-6 month interval at lower levels of the atmosphere. Thin film is not a good media for long-term RH measurements, except in perhaps benign conditions like sensors in museums.

The European project MOZAIC is a “record only” data gathering effort that also uses a Vaisala thin film capacitor for measuring RH on six different A-340s. (Their particular space/time application averages out the random error.) Hermen Smit of Germany has informed me that they recalibrate and/or replace the Vaisala sensor every 500 flight hours (less than a 2-month interval).

2.4 Sensor Wetting

A fourth concern about thin film capacitors in measuring RH is the attribute of sensor wetting. Such capacitors in radiosondes get wet as they ascend through clouds and precipitation – they then register RH values **well over 100 %**. The Vaisala radiosonde internal proprietary software simply assigns the RH value to 100 % when the measured voltage would indicate that it exceeds this amount. Since nature tends to keep the RH with respect to water near 100 % or only slightly above that value, this is not too serious an error **at that instant.** The problem for radiosondes is that the sensor remains wet (until it dries) as it ascends into drier regions, thus giving false readings.

The same situation (though not as serious) occurs for RH measurements on commercial aircraft (ascent, descent and enroute). The drying time of the wet sensor is faster for the aircraft (as it moves faster). However, the sensor wetting could lead to a slight systematic bias in results for ascent versus descent (descent being wetter) – as seen in the Louisville, KY test results (see Fleming, et al, 2002).

2.5 Sensor Reponse Time

A fifth concern about thin film capacitors in measuring RH is the sensor response time. A number of different thin film capacitors were tested with regard to response time in the NCAR study (Hills and Fleming, 1994). The Vaisala sensor had the fastest response time among the RH sensors. A fast response time is important for commercial aircraft sensors because of the speed of the aircraft – even on ascent and descent where the vertical changes in water vapor are extremely important as they effect atmospheric stability – which in turn affects virtually all aviation weather influences: ceiling and visibility, wake vortices, microbursts, thunderstorms, convection turbulence, precipitation at the terminal, and even the wind field due to outflow from mesoscale convective systems. The Vaisala thin film capacitor had the fastest response time in tests at room temperature conditions.

Unfortunately, the response time of thin film capacitors is a function of temperature. Vaisala quotes responses times of 1 second at 0º C, 10 seconds at –20º C, and 100 seconds at –43 º C (Salasmas and Kostomo, 1975). The very slow response times (even slower at the upper flight levels where conditions are –70º C and colder) are not good for depicting cloud conditions. The slow response time leads to some aliasing when a snapshot observation is made, but could generally be accepted for the slowly changing large scale features in the upper troposphere were it not for the other major concern of the Mach number effect. A further problem of slower response times with temperature leads to a complication of ascent versus descent moisture bias – further compounded by temperature variations at different terminals at different times of the year.

3. WVSS-II Mixing Ratio Measurement Results

This section summarizes the laboratory and flight test results of the WVSS-II, which is composed of the SpectraSensors diode laser system and the UCAR air sampler (patent pending), which together make up the WVSS-II atmospheric water vapor measurement system for commercial aircraft, unmanned aerial vehicles (UAVs), and fast moving all terrain vehicles for Homeland Security applications. While the latest figures will be shown here, the reader is urged to view the previous references for a historical perspective and a future reference (Fleming and May, 2004) available soon on this website: http://www.joss.ucar.edu/wvss/, which provides far more detail about the WVSS-II and the predecessor water vapor measurement system of SpectraSensors for their natural gas pipeline business.

The discussion will proceed with the same five negative issues in Section 2 (2.1 through 2.5), showing how each negative aspect is removed by the WVSS-II, and then add a section 3.6 that discusses other important required positive assets for an effective commercial aircraft observing system.

3.1 Mach Number Effect

There is no Mach number effect for a system measuring the atmospheric water vapor mixing ratio. The same number of water molecules is involved whether a sample of air is taken at static or dynamic conditions. The use of Beer's law in providing the mixing ratio result is described in May (1998), Fleming, et al (2002), and in more detail in Fleming and May (2004).

3.2 Calibration Issues

The WVSS-II is easy to calibrate and has been certified over a range of pressure and mixing ratio values in the calibration chamber of SpectraSensors. This calibration chamber has been expanded from its earlier use in the natural gas pipeline business. Figure 3 below shows a typical calibration run where the caption lists the detail. The calibration is exact to a chilled mirror (itself calibrated to a NIST standard).

The use of a fixed frequency laser (1.37 μm) for water vapor measurements via Beer's Law is a non-intrusive measurement – unlike the direct effect of the atmosphere (water vapor and other gases and particulates) on the thin film of the WVSS-I sensor. Calibration is maintained over time – unless the laser power falls to less than 5 % of its original power. The telecommunication quality laser that is used (see next section) has a 20-year lifetime. This is why the prospect of maintenance (re-calibration if needed) is expected only at C-checks (2.5 years apart).

3.3 Loss of Sensitivity Over Time

Much of the discussion in the previous section applies to this issue of sensitivity over time. The nature of the processing method is such that the only loss of sensitivity occurs when the laser power falls below 5 % of its original value. Part of the "smart sensor" software of the WVSS-II sets a quality flag when the sensor falls below 10 % of its original value to give an early warning of potential replacement. The laser used in the WVSS-II is certified as a telecommunication quality laser with a long lifetime.

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 the SpectraSensors "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.

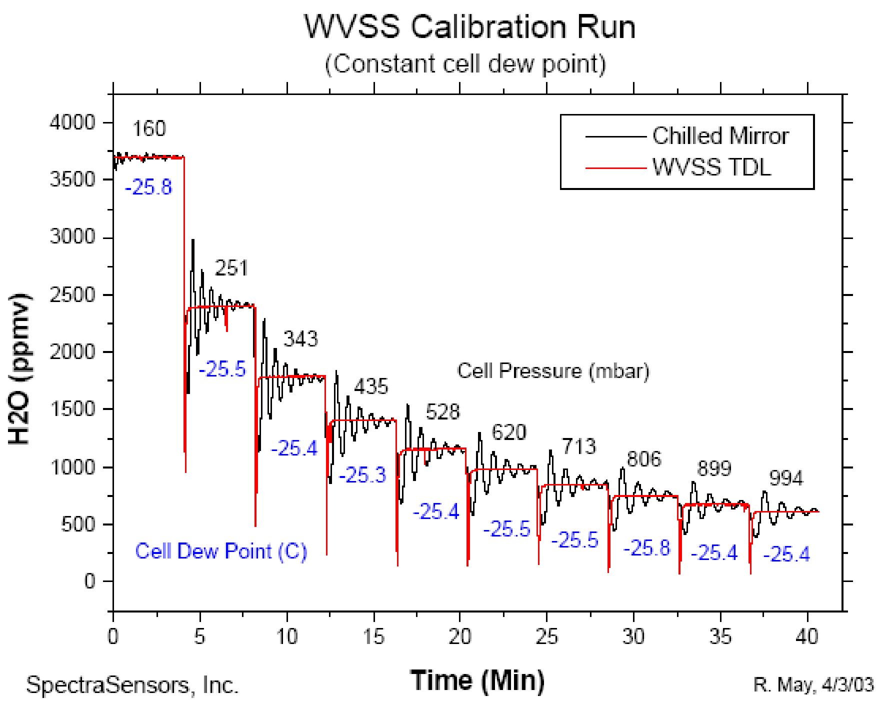


Figure 3: The minimum sensitivity of the WVSS-II is 3 ppmV. This lab run for dry conditions (dew point essentially constant between –25.3 C to –25.8 C) raises pressure from 160 hPa to 994 hPa in steps about 4 min. apart. The chilled mirror dew point (frost point) values are considered truth (chilled mirror calibrated to a NIST 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.

Another aspect of potential sensitivity loss could occur at 40,000 feet where temperatures are extremely cold and the amount of water vapor is quite low. At these conditions, the thin film capacitor on radiosondes are woefully inadequate and severely underestimate the water vapor content – even with Vaisala's temperature correction formulas. This is where the UCAR air sampler is useful in optimizing the performance of diode and quantum cascade lasers. While such lasers would use single mode frequencies chosen to see the trace gas in question (water vapor or a greenhouse gas), **they do not "see" (absorb at that frequency) ice crystals or aerosols.** However, the optical scattering effect on the laser light due to the presence of such particulates could reduce the sensitivity of the measurement. The inertial separator aerodynamic design of the UCAR air sampler removes 80 – 90 % of the heavier particles.

3.4 Sensor Wetting

There is no sensor wetting of the WVSS-II. The laser frequency sees only water vapor – not liquid water. Moreover, the "open path" system designed by Randy May (the architect of the WVSS-II laser system) and used on the NASA ER2 and NASA DC-8 has operated in very wet conditions. The DC-8 operated in a hurricane as did the NOAA P-3 with the WVSS-II (described in Section 3.6 below).

3.5 Sensor Response Time

The WVSS-II has the response time of an optical device, which makes it's response time as fast or faster than the numerical models can handle the water vapor information. The WVSS-II laser spectra are obtained approximately three times per second and six spectra are averaged to produce a unique answer every 2 seconds.

This response time is not a function of temperature as the thin film capacitors. The only limiting factor on response time is the speed of the flow through the measurement cell. For the WVSS-II the UCAR air sampler design and the hose diameter to measurement cell diameter ratios are such that the flow through the cell is approximately 3-6 meters per second. Flow would have to be slower than 20 cm per second to limit the response time. Thus, response time is the same at all altitudes.

3.6 Other Positive Aspects of the WVSS-II to make it Carrier Acceptable

Other aspects of an observing system for commercial aircraft are important to achieve in order **to obtain carrier permission to install the system on his aircraft** – air carriers are in the business of moving people and/or packages and not in the business of making a profit from meteorological observations. Some of these aspects, which have not been directly address above, are summarized below.

Fundamental accuracy must be of high quality in order to justify the entire process of FAA certification, capital cost, installation cost, and subsequent maintenance and communications charges associated with sensors on a commercial aircraft. Fortunately, the diode laser system of Randy May is the most accurate method of measuring water vapor information (May, 1998) and it has become a standard by which other methods are compared (Hinsta, 1999). Figure 4 shows a picture of the WVSS-II mounted on the NOAA P-3 research aircraft. Results compared to the aircraft "standard" chilled mirror are shown in Figure 5 comparing the WVSS-II on the P-3 aircraft with the standard chilled mirror. The WVSS-II was removed from the P-3 after the BAMEX project and recalibrated. It was found to be in the same exact calibration as before the project. The WVSS-II was then put on a second NOAA P-3 and subsequently flown in hurricane Isabel. Comparison results of one of these flights are shown in Figure 6.

The low drag (fuel savings) and the lack of a probe heater (a common failure mode for heated probes is the heater) for the UCAR air sampler were positive attributes contributing to carrier acceptance of the WVSS-II by UPS and Airbus. Measurement pods or other mechanisms hanging beneath the aircraft (as on some research aircraft) are absolutely unacceptable by air carriers (not only the drag aspects, but also the fear of damaging the aircraft by running into such devices with refueling trucks, gateway ramps, “cherry-pickers”, etc, which are always around an aircraft being serviced at a terminal.

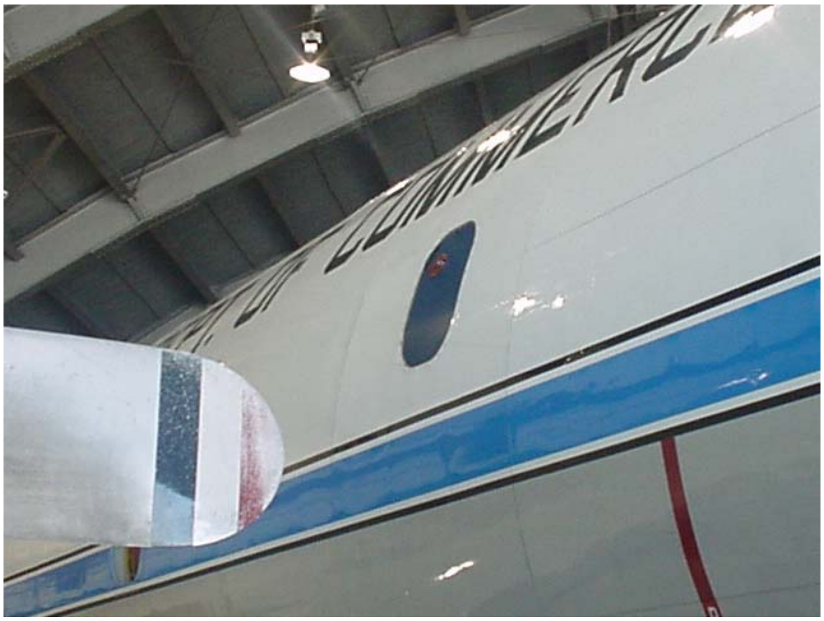
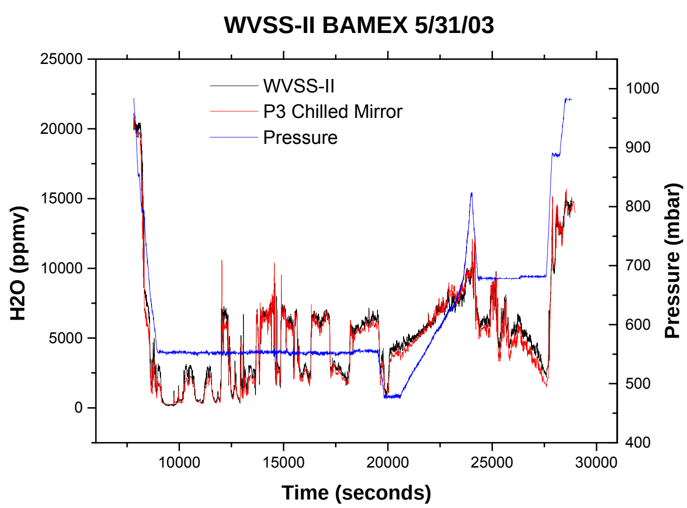


Figure 4: WVSS-II air sampler (red) mounted on blue window plate



BAMEX (Bow Echo and Mesoscale Convective Vortex Experiment)

- Time in seconds on lower horizontal scale.
- Measured static pressure (blue line – reference the right scale) indicates constant flight level between 10,000 and 20,000 seconds; then a series of up and down maneuvers.
- Water vapor measured as mixing ratio in parts per million by volume (ppmV) on left vertical scale.
- Very close match between WVSS-II (black) and NOAA P-3 standard chilled mirror (red).

Figure 5: WVSS-II BAMEX results

A long maintenance interval is extremely desirable for an air carrier. Maintenance (even if paid for by the government) is totally unacceptable if it takes an aircraft off-line from being a revenue producer! The WVSS-II maintenance interval is projected to be what the carriers will accept – only during a C-check when a major overhaul of the aircraft is performed anyway. The C-check time interval varies between aircraft types but is generally in the 2.0 to 2.5 year interval. The forecast of 2.5 years for the WVSS-II is based upon the 20-year laser lifetime and the 20-year air sampler lifetime.

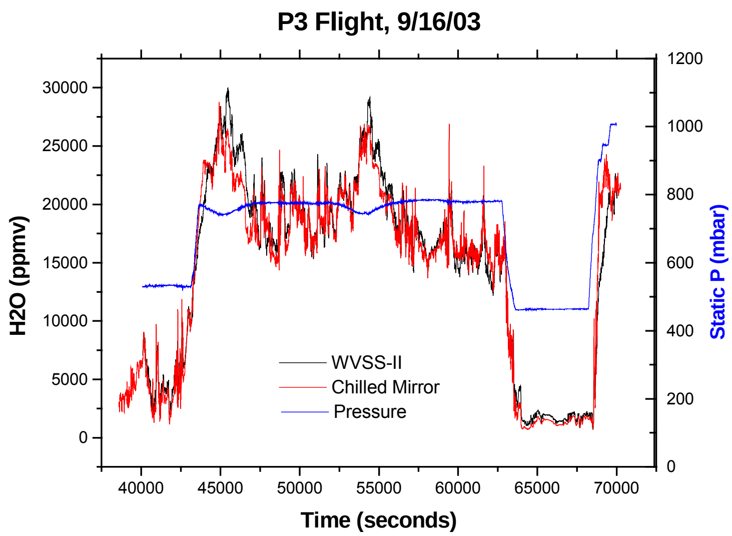


Figure 6: Data comparison of Isabel flight

Low weight, small volume, and low energy use are also carrier requirements of any additional environmental sensor to be added to a commercial aircraft. Most sensors can meet these requirements and the WVSS-II is especially good at all three (see Figure 7).

The uncertainty or error as a percent of signal (Δr/r) for the WVSS-II was calculated in Appendix 3 of Fleming, et al (2002). This produced an uncertainty of 3 % for the conditions stated. This accuracy will be 3-4 % for the entire column (closer to 4 % near 40,000 feet with the UCAR air sampler and the larger measurement cell volume – not yet invented when Appendix 3 was created) – except near the Earth's surface where the accuracy will be only 5 % due to maximum uncertainties in the molecular absorption coefficient for water vapor when pressure and temperature are large. The error structure function needed for 4DDA is thus a simple function of height.

The further success of the regional air carriers and their increased use of ACARS (or a future system like that of the next generation Inmarsat) ensures the viability of the commercial aircraft profiling system of winds, temperatures, and water vapor in real-time. There remains only the will to advance our science to obtain the first mesoscale upper air observing system with the basis of that system the commercial aircraft. Figure 8 indicates that basic system with the red plus signs indicating those airports used by the major and regional air carriers (compared with the current synoptic scale radiosonde sites of the NWS, indicated by blue dots). Implementation of 2400 aircraft of the 5200+ aircraft that fly each day could provide over 100 times as many profiles per day as we currently receive from the radiosondes – this could help the mandated goals at several federal agencies and the needs for Homeland Security (Fleming, 2003).

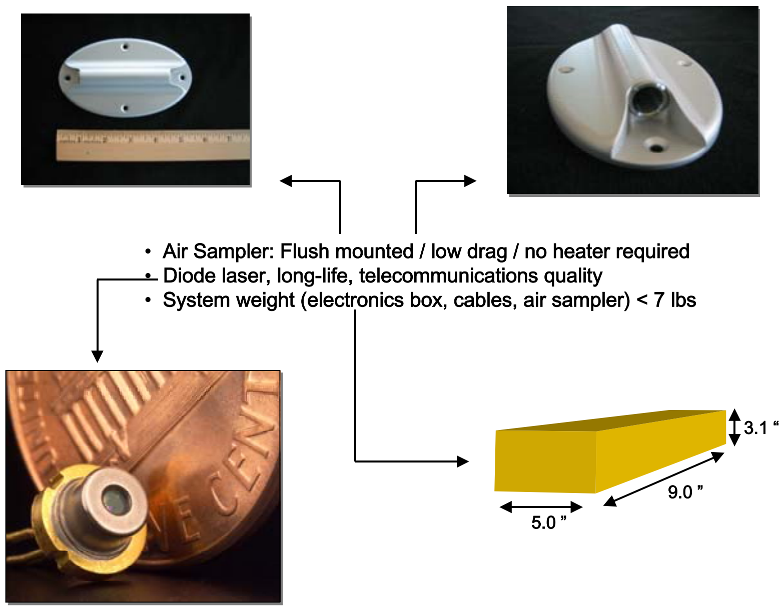


Figure 7: Composite of WVSS-II components

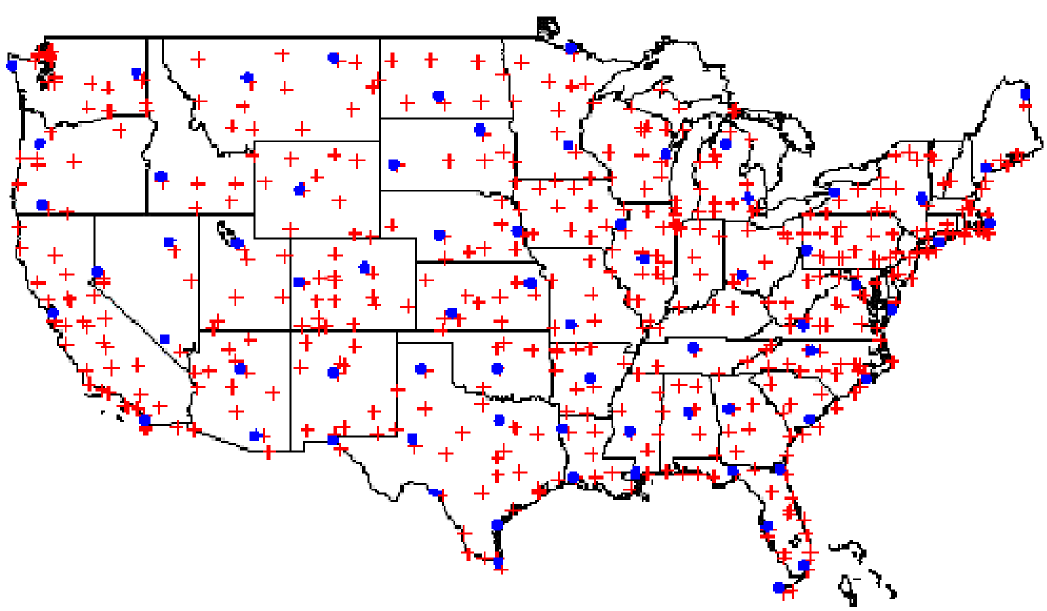


Figure 8: National Mesoscale upper air observing system (see text).

4. Conclusion

The 12-year effort of the author on the WVSS-I and WVSS-II programs has provided many frustrating moments and a few highlights to outweigh the former negatives. One highlight has been observing the changing attitude of the aviation industry over the years that water vapor should indeed be measured by commercial aircraft. The aviation industry in constantly restricted by high capital investment, low profit margins, intense competition, the occasional Gulf War or “9/11” event, and changing fuel costs. The industry is not in a position to add water vapor measurements with their own resources. The government must help!

The WVSS-I program was a proof-of-concept program and served that purpose well. UPS would never have **continued** to carry the WVSS-I for the reasons given in Section 2. They have agreed to carry the WVSS-II and are negotiating for ownership of the units. This is very good! The value of real-time winds and temperature data has already been demonstrated. With the addition of the WVSS-II 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.

One of the more satisfying aspects of the WVSS-II program (including the author’s involvement in the UCAR air sampler) is that this WVSS-II system – exactly as it exists today – can exchange the small diode laser for a future quantum cascade laser (or lasers) and the system can measure other trace species – thus serving two huge societal issues that will continue to dominate our global culture for the foreseeable future – air quality and global climate change. Further, the air sampler can be used on mobile platforms with various small optical and biochip devices for Homeland Security.

Federal agencies need to take action to implement a long overdue mesoscale upper air observing system. Those Federal agencies whose missions’ depend upon the evolution of the atmosphere include NOAA (the NWS and research elements of the organization), the FAA (the operational arm, not just the research component), the Department of Defense (military operations and support for Homeland Security), the Department of Energy (concern for climate change issues), the Environmental Protection Agency (air quality issues), and the Department of Homeland Security (DHS). The Department of Commerce should lead this effort toward a national program for environmental information being efficiently provided by commercial aircraft. Such environmental information would go beyond the current winds and temperatures being provided by some air carriers and add water vapor information, profiles of various trace species important for air quality and global climate change, and eventually include information needed for homeland security.

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