Advancements in the AMDAR Humidity Sensing

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ABSTRACT

The aircraft based humidity sensor type WVSS-II (SpectraSensors Inc., USA) was selected to be tested on a subset of the global AMDAR fleet (Aircraft Meteorological Data Relay). The 2006 version of the WVSS-II was installed in the USA on 25 UPS Boeing B 757 aircraft as well as on three European Airbus A 319 Lufthansa aircraft. The humidity sensors system's output for water vapor mass mixing ratio was integrated into the AMDAR data flow. With the addition of water vapor measurement to AMDAR capable aircraft it is envisaged that aircraft based observations would complement and to a certain extent replace conventional radiosonde sounding systems.

Based on the results from in-flight and climate chamber assessments through 2008, the WVSS-II sensor was reengineered. This re-engineered version has been subject to climate chamber testing at NOAA/NWS (USA) and DWD as well at the Research Centre Juelich (Germany). Upgrades to existing USA fleet of 25 WVSS-II sensors on United Parcel Service (UPS) Boeing B757 aircraft have been completed and 31 new WVSS-II units are being installed on 31 Southwest Airlines Boeing B737 aircraft. Presently in Europe up to 15 units are planned to be installed on a number of E-AMDAR participating aircraft.

Also it has been proposed that an extra flight test program be implemented on a European based research aircraft (FAAM, the BAe 146 platform), currently being used by the British Met Office and the NERC. This trial will allow access to high quality reference humidity measurements performed by precision aircraft mounted scientific equipment as well as to the WVSS-II's raw signal as well as high frequency metadata.

Additionally, results of the laboratory assessments as well as first WVSS-II flight data comparisons with radiosonde profiles are discussed.

1 Forward

The WMO Aircraft Meteorological Data Relay (AMDAR) Program has made significant progress in expanding the number of countries and air carriers participating in AMDAR by facilitating capacity building through by organizing regional workshops and by providing technical leadership through coordination and implementation of standards. However, the AMDAR Program has long recognized full utilization of commercial aircraft as a platform for improving atmospheric understanding will not be achieved if data collected are limited to temperature and wind observations. Towards the goal of more fully describing the atmosphere, it is a high priority for AMDAR to add measurement of water vapor from commercial aircraft to its portfolio. This paper describes AMDAR's progress in realizing this goal.

2 Background

The initial versions of the Water Vapor Sensing System (WVSS-II, versions 1&2) were installed on 25 United Parcel Service (UPS) Boeing 757-200 aircraft in 2005, and on 3 Lufthansa A319 aircraft in 2006. These versions of the WVSS-II were shown to have problems related to internal laser seals and thermal control. In response to these defects, SpectraSensors (SSI) redesigned the sensor resulting in an upgraded WVSS-II (version 3) in 2008. The design changes required an amendment to the Special Type Certification (STC) for existing aircraft in September 2009 (e.g., the B757-200 and the A319 aircraft (pending)), and a new STC was obtained for the B737-300 in January 2010 in preparation for 31 new installations on Southwest Airlines aircraft.

3 Engineering

During 2006-2007, NOAA monitored the performance of the WVSS-II v2 sensor. This version exhibited a range of anomalies, often differing from sensor to sensor, to include dry bias, wet bias, and sensor drift towards a dry bias. SpectraSensors engineers assessed the sources of these issues which were determined to come from leakage of ambient moisture into the laser head cavity and issues related to thermal management of the system[1]. These design changes constitute the 2008 WVSS-II v3 sensor. Future references to WVSSII in this document imply the version 3 design, unless otherwise stated. In additional to these design changes, production process controls were implemented to improve sensor quality including extended laser burn-in and enhanced pressure/temperature, heater and leak testing protocols. SpectraSensors has continued to enhance its factory production environment as demonstrated by the award of an ISO 9001:2000 Certification in 2009.

4 Performance Assessments

The US AMDAR Program has pursued a variety of independent WVSS-II performance monitoring venues, understanding that no single assessment provides a full picture of performance. These assessments are described in section 4 of this paper.

4.1 Factory

During 2008-2009, SpectraSensors and NOAA National Weather Service (NWS) Test Engineers coordinated test protocols, reference equipment and testbed setup configuration. Three System Equipment Boxes (SEBs) where tested at the SSI factory in Rancho Cucamonga, California, then shipped to the NWS Test Facility in Sterling, Virginia, for further testing. Both SpectraSensors and NWS used the Edgetech RH373 chilled mirror hygrometer as a reference sensor. Likewise, the German Weather Service (DWD) used a MBW 373 chilled mirror hydrometer for their chamber tests of the WVSS-II. Both Sterling and DWD chamber tests are described in this paper.

4.2 Chamber Tests

In addition to factory checks with reference sensors, independent chamber tests were conducted by DWD and NWS, culminating with reports in September 2009 and October 2009, respectively.

4.2.1 NWS Sterling Results

The NWS Sterling, Virginia, Test Facility chamber setup includes a Thunder Scientific 4500 humidity generator and an Edgetech RH373 chilled mirror hygrometer. Data were collected at 18 points, using a range of pressures (ambient (surface) to 200 hPa), temperatures (- 59.2 °C to ambient (surface)) and humidities (15 % to 95 %) to simulate atmospheric conditions encountered by commercial jet aircraft (operating at 13 km AGL).

The WVSS-II performed within specifications at all test points when the flow rate was five litres per minute (**Fig. 1**). Even at four and six litres per minute, the results are similar and repeatable except the first test point at 200 hPa. Overall, the WVSS-II sensor performed well under most of the test conditions. Output of the reference sensors was not very steady at higher flow rates and lower pressures taking longer times to stabilize when exposed to constant humidity. The differences between the chilled mirror (RH373) and WVSS-II output may be explained by the very fast response of the laser in the WVSS-II (and relatively slow response of the chilled mirror).

Fig. 1: Chamber results, % difference in ppmv, between WVSS-II/TS4500 (**blue**), WVSS-II / RH373 (**green**) and dew / frost points (red)

4.2.2 DWD and Forschungszentrum Jülich (FZJ) Results

The DWD climate chamber consists of a pressure and humidity controlled vessel inside a larger temperature controlled chamber. The WVSS-II was installed inside the temperature controlled chamber and the System Electronics Box (SEB) was thermally insulated to keep the operating temperature within the range specified by the manufacturer SSI. This configuration is equivalent to the arrangement in a typical aircraft installation. The sampled air was pumped inside a closed loop containing the SEB, an MBW 373 chilled mirror hygrometer, and the inner vessel in which pressure and humidity are controlled. A supply of a well stabilized mixture of dry and wet air comes from outside and is cooled to internal temperature while passing through a long pipe coil. Pressure control is achieved by aligning inflow against outflow.

The FZJ climate chamber (http://www.fz-juelich.de/icg/icg-ii/esf) is a stainless steel vacuum chamber with a volume of 500 litres (80 x 80 x 80 cm). Pressure and temperature are computer controlled to simulate temperature, pressure and humidities which are typically encountered in the troposphere, including tropopause, and lower stratosphere (Smit et al., 2000). The WVSS-II instrument is installed in a styrofoam box (temperature controlled at 20 ^{o}C) inside the simulation chamber. With a small electrical driven pump a sampling volume air flow of about 3 l / min was forced through the WVSS-II. An accurate Lyman (α) fluorescence hygrometer [Kley et al., 1978] low specific humidities (0.001 - 1 g / kg, accuracy ± 4 %), while a dew/frost point hygrometer (General Eastern, Type D1311R with accuracy ± 0.5 K) served as reference at larger specific humidities (1 - 40 g/kg).

Several simulation runs were conducted in the chamber whereby the water vapor mixing ratio was varied from 30 g / kg downwards to 0.001 g / kg while pressure and temperature were adjusted from 1000 hPa and 300 K through 200 hPa and 200 K, typically for real atmospheric conditions between surface and 12 km altitude.

For the complete range of the climate chamber's humidity values the WVSS-II correct and stable responses. Fig 2 shows that the results are near by the ideal line. Even at an extremely low humidity value of 0.003 g/kg the WVSS-II accurate and precise measurements. Because of some actual limits for very low pressure operation of the chamber these values were obtained in the range of 800 to 1050 hPa. The most extreme set point in the NOAA test (not depicted in Figure 2) at 200 hPa and 24 ppmv has been emulated at 1032 hPa by 0.003 g/kg (5 ppmv) to get to the same vapor density as the intrinsic physical parameter for the absorption. The detection limit seems to be lower than that of the previous version (having been at about 0.05 g/kg at ground pressure). With the humidity values actually being reproducible by the DWD climate chamber the lower sensitivity bound of the WVSS-II unit S/N 0302 could not be reached.

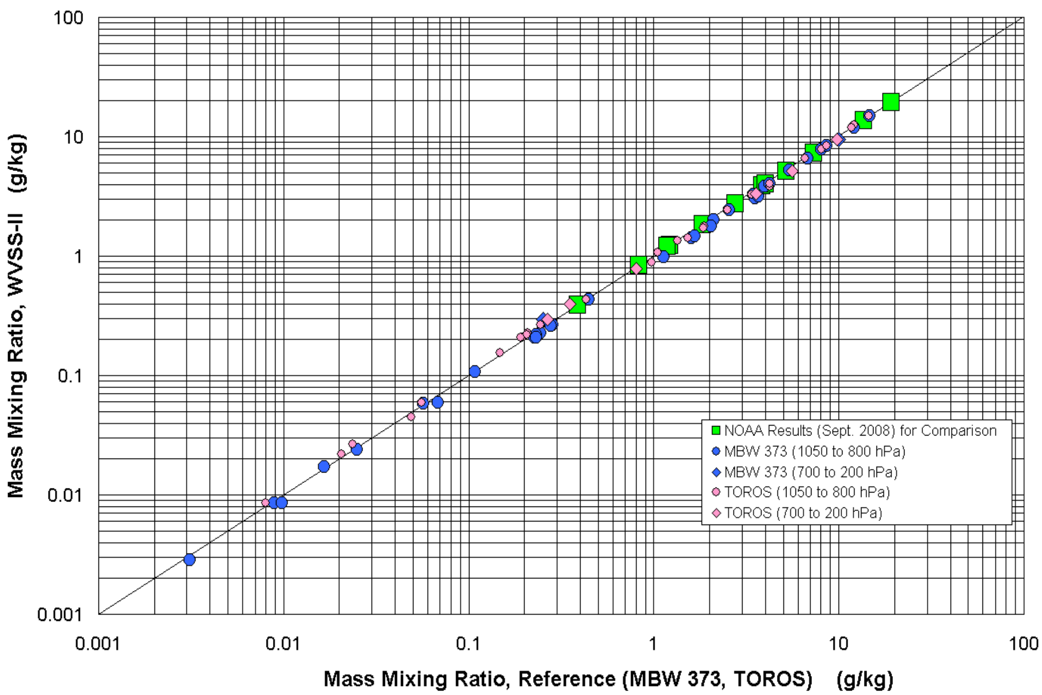


Fig. 2: The WVSS-II's mixing ratio readings plotted in a log-log diagram against the climate chamber's reference measurements. The differently marked data points distinguish

- the reference sources (MBW 373, TOROS)
- the air pressure ranges (1050 to 800 hPa, 700 to 200 hPa)
- the NOAA test results of September 2008.

Figure 3 provides relative deviations from the reference values and shows:

- in the range of 1 to 10 g/kg a small tendency to a dry bias of around 5 to 7 %,
- below 0.5 g/kg most of the readings keep within ± 10 %.

Considering the accuracies especially at the low humidity values, we have to keep in mind the limits of the absolute references themselves: uncertainties between 0.1 and 0.8 K in the dew point or frost point could lead to deviations of up to 10 % at a mixing ratio level of 0.1 g/kg.

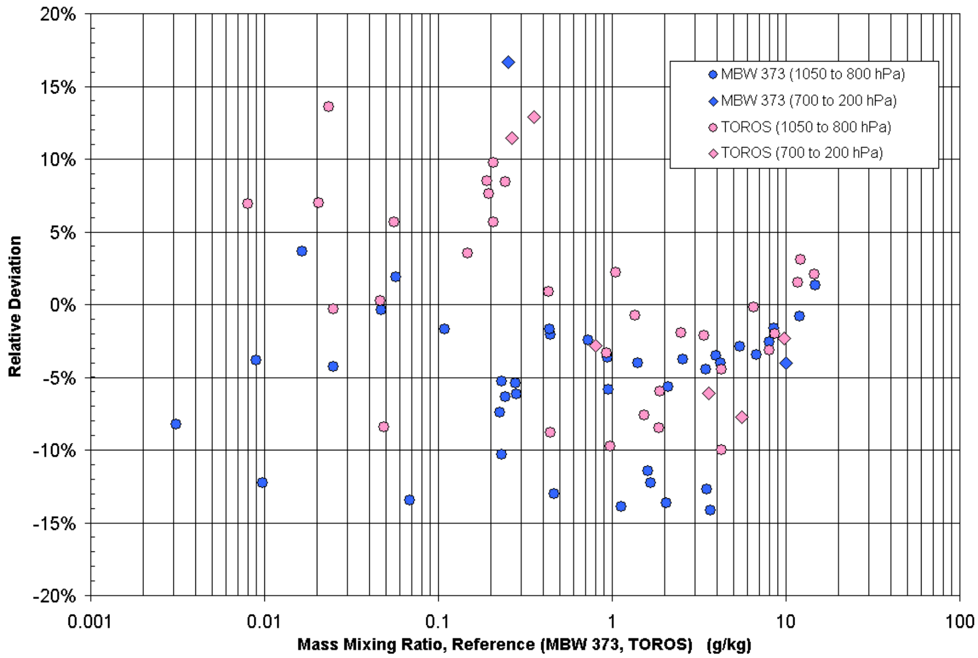


Fig. 3: The relative deviations of the WVSS-II values against the references.
The differently marked data points distinguish
- the reference sources (MBW 373, TOROS)
- the air pressure ranges (1050 to 800 hPa, 700 to 200 hPa).

The chamber experiments show that WVSS-II tracks humidity structures very well, whereby the performance at low relative humidities as well as at almost saturated conditions is virtually the same. A comparison of the WVSS-II versus the reference hygrometers is shown in Fig 4. At mixing ratio values between 0.05 g / kg (≈ 80 ppmv) and 20 g / kg (≈ 30,000 ppmv) the WVSS-II performs well with a relative uncertainty better than ± (5 - 10) %. However, at low specific humidities below 0.05 g / kg (≈ 80 ppmv) the deviations of the WVSS-II compared to the Lyman (α) are getting larger and reaching the detection limit at about 0.02 g / kg (≈ 30 ppmv) at air pressure of 200 hPa.

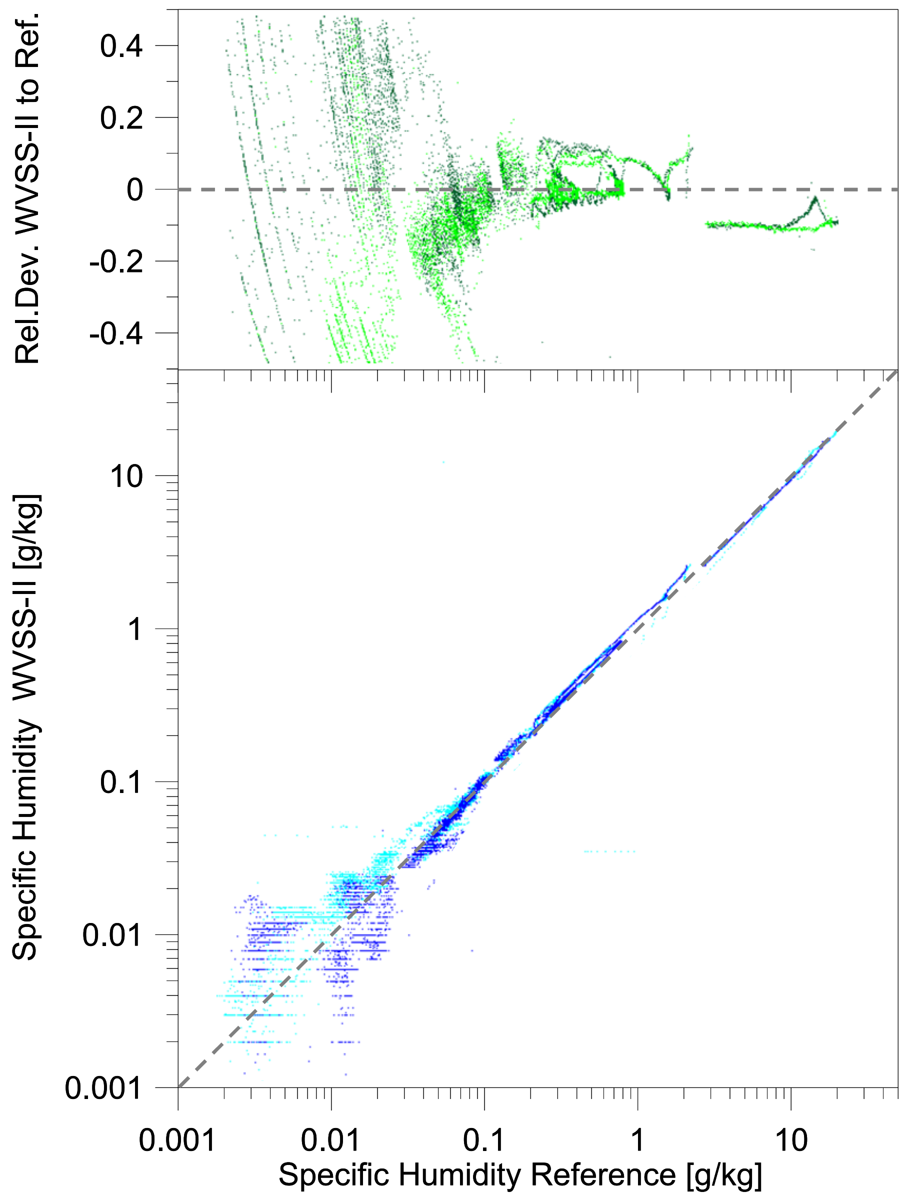


Fig. 4: Comparison WVSS-II versus Lyman (α) fluorescence hygrometer (0.001 - 1 g/kg) and dew / frost point hygrometer (General Eastern, Type D1311R, 1 - 40 g / kg) obtained from 2 simulation runs made in the FZJ climate chamber (http://www.fz-juelich.de/icg/icg-ii/esf) in July 2010.

The chamber experiments have shown that the WVSS-II performs well with a relative uncertainty of ± (5 - 10) %. For humidity levels between 20 g / kg (≈ 30,000 ppmv) and 0.05 g / kg (≈ 80 ppmv) typical for the lower and middle troposphere the performance is good with relative accuracy of WVSS-II is ± (5 - 10) %. However, particularly at upper tropospheric conditions where water vapor mixing ratios are well below 0.05 g / kg the accuracy of WVSS-II is declining down to the detection limit of about 0.02 g / kg.

The smallest mixing ratio value taken during the DWD test was at m_0 = 0.0031 g/kg (5 ppmv) at an air pressure p_0 = 1032 hPa and a temperature of - 54.2 °C. The corresponding water vapor density ρ_{H2O} as the primary physical parameter for the absorption at the sampling tube's temperature T_{Tube} = 308.65 K (+ 35.5 °C) then is

$$\rho_{H2O} = \frac{m_0\ p_0}{T_{Tube}\left(R_{dry} + m_0\ R_{H2O}\right)} = 3.6\ \frac{mg}{m^3}$$

with: R_{dry} = 287.0586 J / kg / K (gas constant of dry air)
R_{H2O} = 461.525 J / kg / K (gas constant of water vapor)

The WVSS-II detection limit seems to be equal to or lower than this value. If we conserve this vapor density and calculate back to a mixing ratio m_{UA} at the upper atmosphere level of p_{UA} = 200 hPa , assuming the same T_{Tube} value, we get:

$$m_{UA} \approx m_0\ \frac{p_0}{p_{UA}} = 0.016\ \frac{g}{kg} \quad (\equiv\ 26\ ppmv)$$

This humidity indication or even a lower one should be verifiable with the WVSS-II at the flight level of 200 hPa as the DWD climate chamber did with 0.0031 g/kg at ground pressure. At this pressure and with the ISA-Stratosphere temperature of – 56.5 °C the tested WVSS-II unit can do the traceable measurement of a relative humidity of 30 % (here: referred to the saturation pressure over ice).

These chamber results indicate that performance of the WVSS-II sensor is sufficiently accurate for airborne humidity measurements in the lower and middle troposphere. For upper tropospheric or lower stratospheric measurements the sensitivity, detection limit, precision and accuracy of WVSS-II are on the borderline for use in the region of the upper troposphere and lower stratosphere.

4.3 Inter-comparisons

4.3.1 CIMSS Field Assessments

The Cooperative Institute for Meteorological Satellite Studies (CIMSS), through a Cooperative Institute grant from NOAA, has been conducting inter-comparisons of aircraft observation data against its mobile atmospheric laboratory sensor suite, AERIBAGO, since 2005. In the past year, the AERIBAGO has collected validation data for comparison against the WVSS-II observations, using RS92 rawinsondes, at Rockford, Illinois, (KRFD) in November 2009, April-May 2010 and in August 2010. These deployments have resulted in multiple sounding "pairs" under a variety of air masses and moisture environments. Figure 5 is an example of the WVSS-II / RS92 inter-comparison data collected during these field deployments.

The analysis of data from these deployments is preliminary with a final report expected later in 2010, but preliminary analysis of data collected from the spring 2010 deployment show the RS92 rawinsonde data match WVSS-II data very closely with random differences ranging from 0.2 to 0.5 g/kg at all levels. In the case of the spring 2010 deployment, WVSS-II data show a slight moist bias, ranging from 0.1 g/kg to 0.4 g/kg. When affects of aircraft (warm) temperature bias is considered, WVSS-II statistics show a moist bias of 2.8 % and 10.8 % standard deviation for RH.

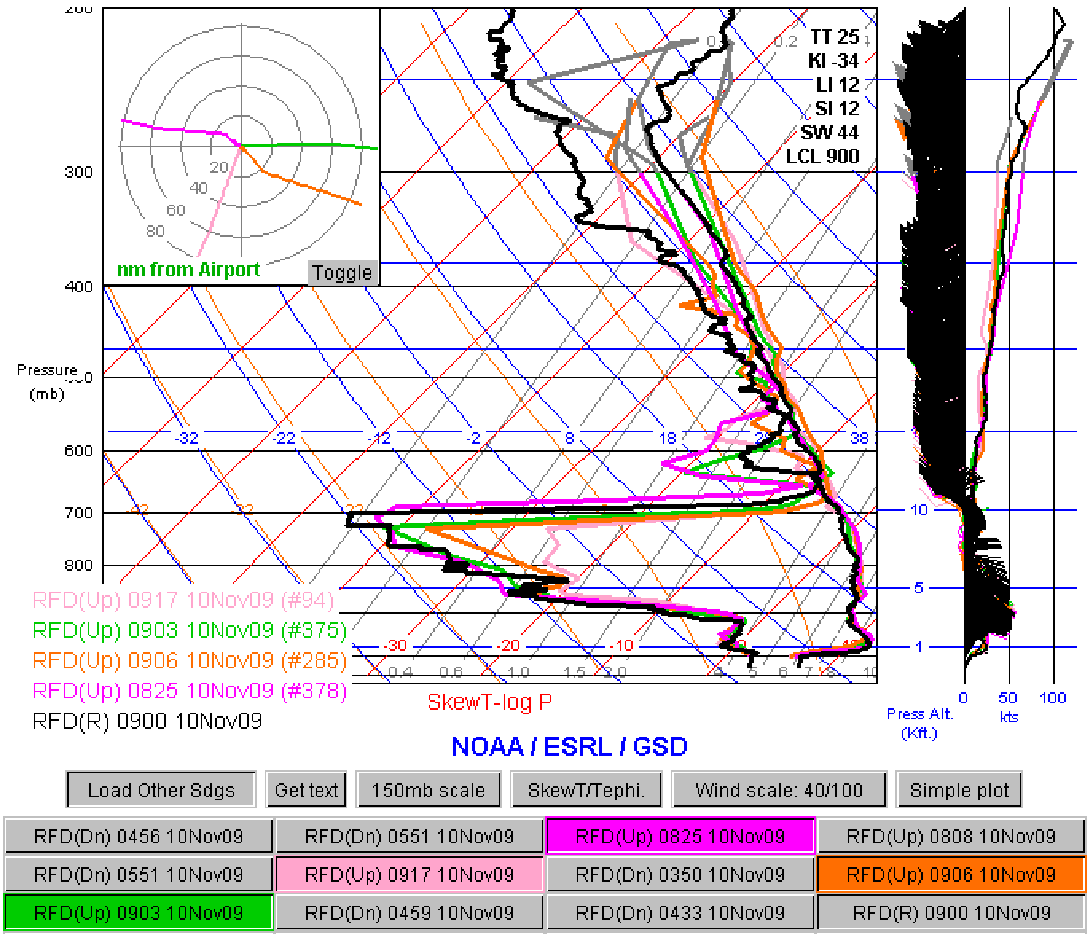


Fig. 5: WVSS-II (4 aircraft) / RS92 Rawinsonde SKEW-T depiction, November 2009, from Rockford, IL (KRFD)

4.3.2 GPS-Met

Integrated (total atmospheric column) Precipitable Water (IPW) data can be retrieved from tropospheric signal delays measured using dual-frequency GPS receivers (Bevis et al., 1992) in near real-time with sub-mm level precision, Gutman, et al, 2004a,b). The World Meteorological Organization (WMO) has recognized IPW from GPS-Met processing as climate quality moisture data (WMO GCOS-92, 2004), and it is the objective of the US AMDAR Program to use these data as a reference moisture data source for WVSS-II, and the GCOS Reference Upper-Air Network (GRUAN) Program incorporates ground-base GPS/GNSS receivers as part of the Tier-1 (mandatory) configuration at all reference sites.

A relational database storing IPW calculated from AMDAR aircraft (WVSS-II and TAMDAR), radiosonde, model (RUC and GFS) and GPS-Met sources was established in

2008 by NOAA's Earth System Research Laboratory in Boulder, Colorado USA. This database was used to compare GPS-Met IPW data from the Louisville GPS-Met station (LOU6) with IPW data derived from WVSSII-v3 aircraft flying from Louisville International Airport (KSDF) in November-December 2009. During this period, 95 pairs of GPS-Met/WVSSII IPW data meeting constraints of time (within 15 minutes of aircraft sounding), and linear distance between the aircraft and the GPS-Met station, and vertical domain (WVSSII soundings must extend through 500 hPa) were collected from 8 different UPS B757 aircraft. In this sample it was found that, after removing outlier points, the slope of fit linear line is 1.0, with a 3% negative bias for WVSSII as compared with GPS-Met IPW (Fig. 5.a and 5.b). A possible explanation for the WVSSII dry bias is an issue resulting from "incomplete" moisture soundings where the aircraft levelled-off before capturing the full extent of atmospheric moisture.

A.. B.

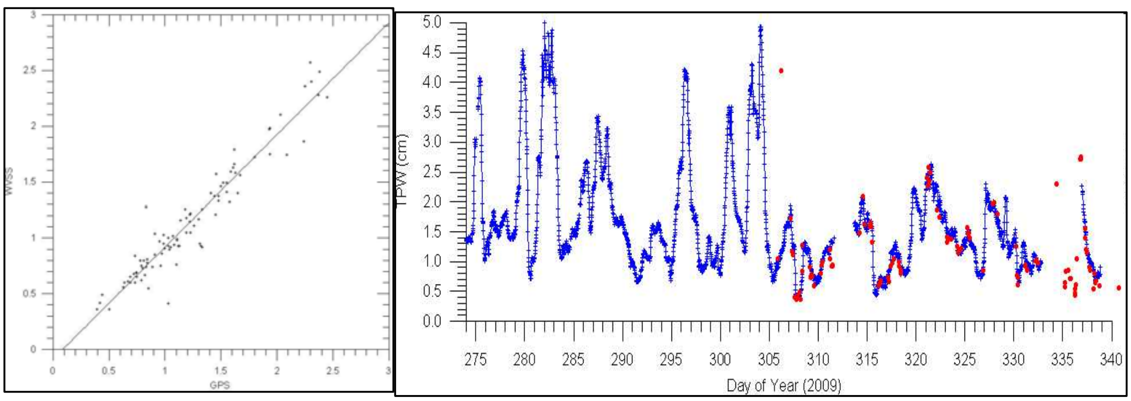


Fig. 6: A. GPS-Met / WVSS-II Correlation, and
B. GPS-Met / WVSS-II Time Series (credit: Seth Gutman)

4.3.3 ASOS

The USA Automated Surface Observing System (ASOS) includes about 1,000 stations, operated by NOAA, the Federal Aviation Administration (FAA) and the Department of Defence (DoD). The current ASOS suite includes a Vaisala DTS1 capacitive relative humidity sensor, which is based on the Vaisala HMP243 sensor (Dover, 2004). Airport dew point observations are calculated from ASOS temperature and relative humidity observations.

As an independent check on WVSS-II performance, ASOS dew point observations are used to monitor WVSS-II performance for the lowest portion of the sounding, on final approach and during take-off. Sources for error with this assessment method include the calculated nature of the ASOS dew point verses WVSS-II mixing ratio, observation time mis-matches of up to 30 minutes and elevation differences between the aircraft and ASOS location. Care must be taken to ensure WVSS-II data are limited to situations when the aircraft is moving as the WVSS-II is passively aspirated.

Randy Baker, UPS Airlines Lead Meteorologist, collected a sample time-matched WVSS-II / ASOS dew point data for ASOS in 2009 at KSDF airport, which Ralph Petersen, University of Wisconsin Researcher, processed; the results of this analysis are shown in Fig 7.. According to Dr. Petersen, the results (Figure 7) indicate that, for observations taken at the surface with little or no aircraft motion, the WVSS-II data have almost no systematic error (Bias) and extremely small random error (Standard Deviation - StDev). In addition, the StDev in Dewpoint Temperatures derived from the fundamental mixing ratio reports is ~ 50 % that of the aircraft Temperature reports, and again without bias. As such, any biases noted in derived Relative Humidity (RH) are almost entirely the result of errors in temperature observations and the random RH error of ~ 60 - 70 % is primarily the result of aircraft temperature errors. When the temperature error components are removed, the moisture errors account for an RH error of < 4 %, a value which exceeds the accuracy of most rawinsonde sensors and all WMO requirements.

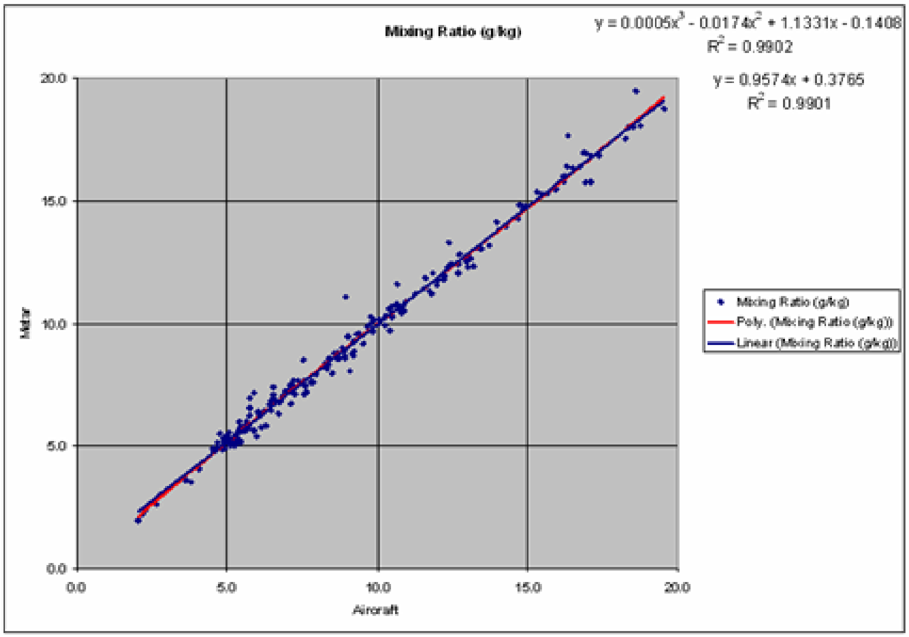


Fig. 7: Correlation between ASOS and WVSS-II mixing ratio (Credit: Randy Baker and Ralph Petersen)

4.3.4 Model

Both the NOAA National Centers for Environmental Prediction (NCEP) and NOAA Earth System Research Laboratory (ESRL) monitor observation quality for use in data assimilation into numerical model analysis. These data, and the resulting bias and standard deviation statistics, are used as an additional check on USA AMDAR observations. Specifically, ESRL maintains a seven day running quality control statistics, for the Rapid Update Cycle (RUC) model analysis which are monitored closely.

The accuracy of the model moisture analysis is not always perfect, and there is the potential for a substantial difference between the grid point volumetric representativeness of moisture and the representativeness of AMDAR in situ "point" aircraft observations. Thus even with "perfect" model analysis and in situ observations, a standard deviation of 12 - 20 % is nominally observed but is not regarded as a concern. True also is the possibility for model analyzes to have yearly and seasonal biases, making the model analysis an imperfect source for "truth". With these caveats in mind, model analyses have been found to be a useful tool in monitoring short- and long-term performance trends.

The USA AMDAR Program used the ESRL aircraft/model analysis (RUC) statistics to monitor the performance of the first 20 WVSS-II sensors installed on UPS aircraft to determine the similarity of the WVSS-II fleet. The WVSS-II fleet statistics exhibited a small negative bias cluster (0 % to - 5 % RH against the RUC analysis) with a standard deviation of 12 % - 20 % (see Figure 8). This sensor to sensor consistency across the WVSS-II fleet as compared with numerical models support the case that SpectraSensors factory manufacturing process improvements are yielding results.

Experience with the WVSS-II sensors has shown that persistent large bias sensor statistics (>+/-10%), and standard deviations (>25) need to be examined with greater rigor. Model bias and standard deviation statistics have helped to identify blockages in the WVSS-II intake and failures of the SEB (2 cases).

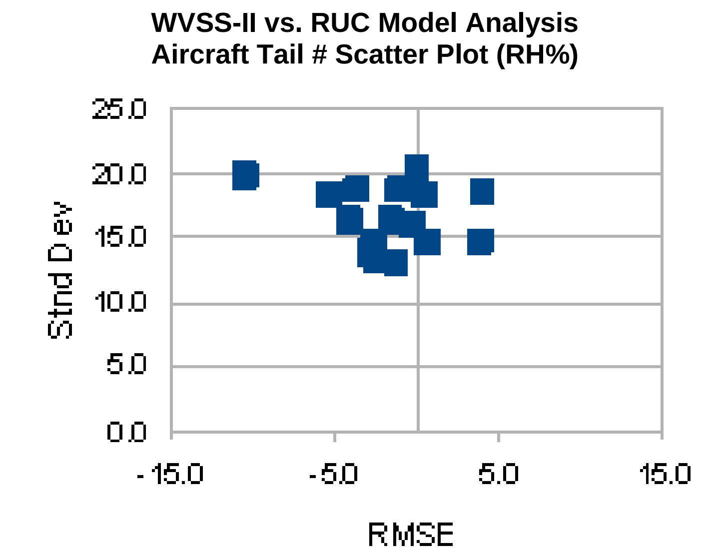
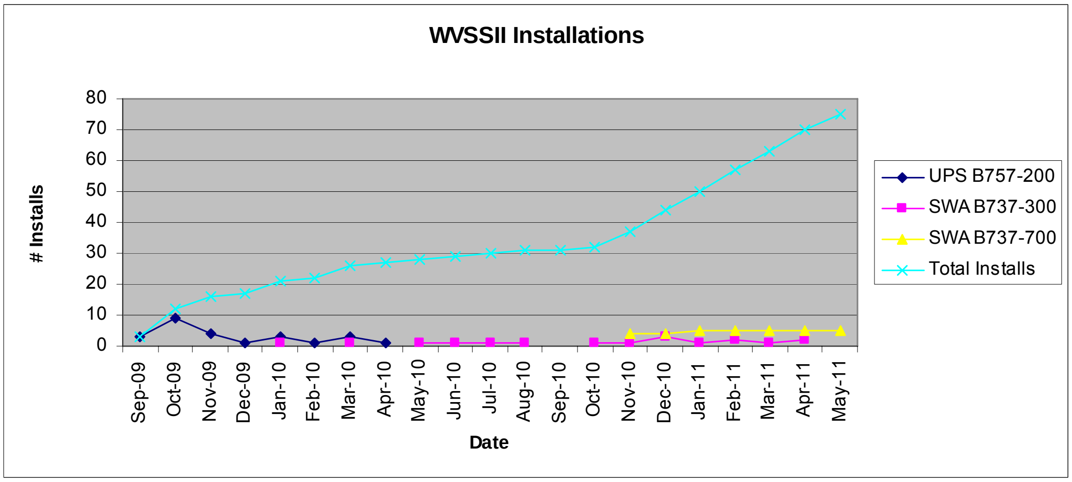


Fig. 8: Rapid Update Cycle (RUC)/ WVSS-II analysis derived statistics for January 2010 (Source: NOAA/OAR/ESRL/GSD, http://amdar.noaa.gov/RUC_amdar/7day_stats.cgi?c=bias_RH)

5 Deployments

The first ARINC/SpectraSensors contract called for 56 installations, 25 sensors on UPS B757-200 aircraft (completed in April 2010), and another 31 sensors installed on Southwest Airlines B737-300 aircraft. As of August 2010, 5 of 31 Southwest installations have been completed. The slow rate of B737-300 installs is a function of the limited -300 series aircraft in the Southwest's fleet; with just 30 total -300 airframes available, one installation per month is possible.

Based on the successful re-design of the WVSS-II, the award of STC for installation of the WVSS-II on the B757-200 and B737-300 aircraft, and resulting nominal performance of WVSS-II as compared to chamber tests, model analysis, GPS-Met, radiosonde, and ASOS moisture data, NOAA awarded ARINC/SpectraSensors a second contract in June 2010 for additional installations of the WVSS-II. This contract allows for options for an additional 36 WVSS-II to be installed on Southwest Airlines B737 aircraft. This contract funds an additional STC for the B737-700 aircraft, of which Southwest Airlines has 300 airframes. Based on the expected award of the STC for the B737-700 series aircraft in late 2010, the deployment schedule is shown in Figure 9. The -700 series STC allows for ramping up installations from 1 to 6 airframes per month, allowing for 92 aircraft to be instrumented with the WVSS-II sensor by summer 2011. The first five Southwest Airlines aircraft to be instrumented with WVSS-II have been workhorses, often flying to more than 8 airports per day, generating over 16 soundings. With 92 WVSS-II aircraft, over 1,000 soundings per day could be generated from UPS and Southwest airframes.



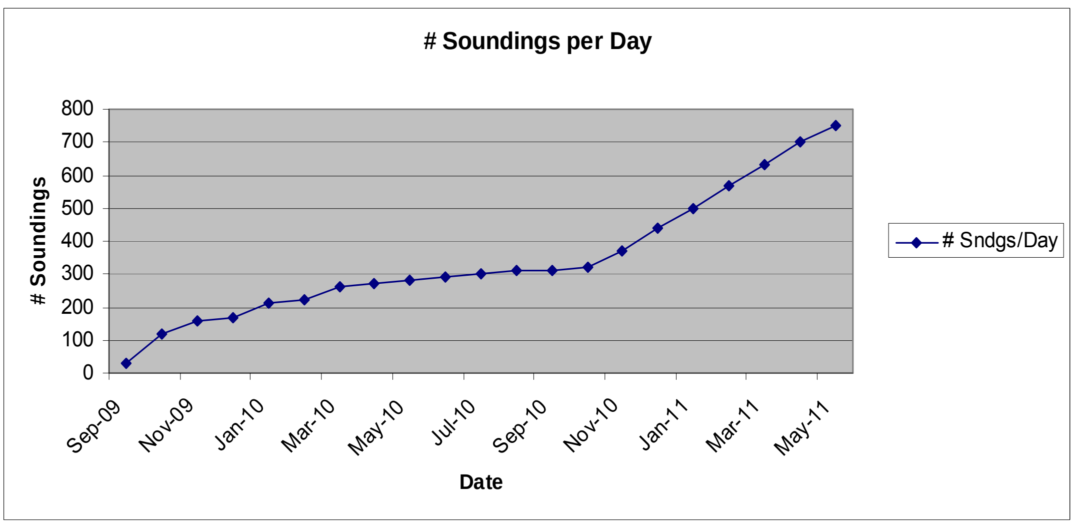


Fig. 9: Current and planned WVSS-II installations and soundings by NOAA

EUMETNET-AMDAR currently operates 3 units of the WVSS-II version 2 on Lufthansa Airbus A319. The experience with these instruments is described by a report from A. Hoff (Oct. 2009). The technical performance of that WVSS-II generation has shown some limits in the long term signal stability leading to a lack in the relative accuracy of definitely more than 10 %.

In 2011 and 2012 EUMETNET-AMDAR plans to replace the old units and to equip in a first step 6 additional aircraft of the Lufthansa fleet with the new WVSS-II v3. Shortly after, another 6 units will follow. Future deployments are contingent upon available funding.

6 Future Activities

6.1 In-flight Assessments

Chamber investigations were performed under well defined, ideal laboratory conditions with the goal to determine the instrumental performance of the detector itself, e.g., sensitivity, detection limit, precision and accuracy. In-flight operation will encounter a variety of new, presently not well quantified, uncertainty sources such as, increased flow rates, air sampling, airport-pollution, and mechanical and thermal stress. Therefore, in-flight assessment of the WVSS-II instrument performance against advanced reference hygrometers is required as a compliment to chamber tests; two such assessments are planned:

- On behalf of EUMETNET-AMDAR (E-AMDAR), the UK Met Office plans flight tests in last quarter of 2010 of the WVSS-II on the research aircraft, a BAe146, belonging to the Facility for Airborne Atmospheric Measurements (FAAM). The BAe146 has an operating ceiling of up to 35,000 ft, suitable for upper tropospheric research.
- NOAA is working with the Atmospheric Turbulence and Diffusion Division of Air Resources Laboratory to integrate the WVSS-II on the University of Tennessee Space Institute's (UTSI) Piper Navaho, which has an operating ceiling of 20,000 ft. The UTSI flight tests would compliment the UK Met Office research by sampling the lower troposphere in maritime Tropical airmass of the southeast USA, where moisture in excess of 15 g/kg is routine. This assessment is planned to occur in the first quarter of 2011.

6.2 Coding and Metadata

Loss of precision is an issue with the dissemination of water vapor (mixing ratio) data, within the ARINC 620 protocol, aircraft communications addressing and reporting system, and in BUFR, particularly in very dry atmosphere of the upper troposphere. The AMDAR Panel is working with codes configuration management teams to improve this situation. In addition to precision concerns, automated "flagging" of suspect moisture data in BUFR is also being pursued.

6.3 Monitoring

Robust monitoring of water vapor observations from aircraft is also being addressed through use of integrated observing techniques, such as through monitoring of AMDAR derived IPW using GPS-Met data as a reference.

6.4 Extending Sensor Performance

In the last quarter of 2010, SpectraSensors was awarded a phase I Small Business Innovation Research (SBIR) for design work supporting extending the WVSS-II sensitivity from the current threshold of about 50 ppmv to climatic minimums of moisture near 1 ppmv. This SBIR research topic was solicited by NOAA in response to chamber results indicating sensor limitations with the low end of atmospheric moisture. SpectraSensors has experience with ppbv sensitivity sensors in the gas and petroleum industry using Tunable Diode Lasers with more responsive wavelengths and greater sample path length.

7 Summary

AMDAR is increasingly seen as an essential operational component of the World Weather Watch (WWW). The recent activities by the AMDAR community have provided the foundation for including moisture from commercial aircraft as an integral component of the AMDAR parameter suite.

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