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JOINT MEETING:
CBS EXPERT TEAM ON AIRCRAFT BASED OBSERVATIONS
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AND
AMDAR PANEL
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PROJECTS, PLANNING AND WORK PROGRAMME

AMDAR Science and Technical Development

Water Vapor Sensor Implementation Plan

(Submitted by the Secretariat)

SUMMARY AND PURPOSE OF DOCUMENT

To summarise the current status of the technological and operational development of a water vapour measurement capability for AMDAR and to make recommendations on the process towards winder implementation.

ACTION PROPOSED

1. The Joint Meeting is invited to note the information contained in the document.
2. The Joint Meeting is invited to consider the recommendations made in the document.

BACKGROUND

1. The AMDAR Panel and the aircraft observations community in general has been involved in and closely followed the technological research and development of water vapor sensing technology for aircraft platforms over the past decade with a view to the possible implementation of such a sensor as a part of the operational AMDAR Programme.

2. It is considered and expected that the successful development of a water vapor sensing capability for aircraft platforms offers the potential for significant improvement to the global coverage of upper air profiling of atmospheric water vapor content, both spatially and temporally and would have a large and significant impact on many meteorological application areas including numerical weather prediction systems, aeronautical and public weather forecasting and climate monitoring.

3. Additionally, it is expected that such a development offers the opportunity for NMHSs to consider significant changes to the configuration of their operational upper air measurement networks leading to large improvements in upper air network efficiency and optimization.

4. Most of the efforts and success in this area have centered on the research, development and testing that has lead to the production of the Water Vapor Sensing System, second generation (WVSS-II) by SpectraSensors Inc. The AMDAR Panel has monitored, supported and contributed to this development in the interests of its Members.

5. Appendix 1 provides a summary history of the Panel’s relationship with the WVSS-II development over most of the past decade up to the end of 2009.

RECENT DEVELOPMENTS

6. The following summarises the major activities that have occurred in relation to the WVSS-II sensor development over the past two years.

Contracts and Deployment

7. The USA NWS has continued to operate contracts with ARINC that includes subcontractors United Parcel Service (UPS) airline and Southwest Airlines (SWA) for the implementation of WVSS-II third generation systems (WVSS-II-v3) on their B757 and B737 fleets. As at November 2010, 25 WVSS-II-v3 systems had been installed on UPS B757 aircraft and 4 SWA B737 aircraft. At the current time, the 25 UPS aircraft continue to operate and 29 SWA B737 aircraft have been fitted. These aircraft provide around 18,000 observations of water vapor per day.

8. Three WVSS-II-v2 sensors have continued to be operated by Lufthansa Airlines on A319 aircraft under contract with E-AMDAR, with contract negotiations with Lufthansa for their upgrade to WVSS-IIv3 and a further 6 additional aircraft equipped, nearly finalized.

Testing and Comparison

Aircraft Platforms

9. WVSS-II-v3 sensors have been flown on two research aircraft over 2011 allowing comparison with water vapor measurement standards.

10. Two differently configured WVSS-II-v3 systems have been deployed on the BAe 146 aircraft operated by FAAM (Facility for Airborne Atmospheric Measurements, UK). In “piggy-back” mode, the WVSS-II units are operated together with reference humidity instruments during routinely scheduled campaigns. Whilst the first unit has been operated in standard configuration, the second instrument has been configured to test an alternate sample air inlet. The second configuration provides an increased pressure in the sample gas flow to allow an extension of the instrument’s test range by 100 hPa or more. Preliminary results from the first test periods conducted were very good with an updated report expected to be made available in October or November 2011.

11. In a second trial, two WVSS-II units have been deployed on a Lear Jet 35 operated on behalf of EUFAR (European Facility for Airborne Research) and comparison made with several sophisticated humidity measurement techniques as part of DENCHAR (Development and Evaluation of Novel Compact Hygrometer for Airborne Research). Initial results show a consistency of the instrument’s performance with the climate chamber.

Assessment of WVSS-II vs. Rawinsonde data during 2009-2010 at Rockford, IL, USA

12. The Cooperative Institute for Meteorological Satellite Studies (CIMSS) University of Wisconsin-Madison (UW) has continued intercomparison analyses of the co-located rawinsonde (RS-92) and WVSS-II-v3 data collected over 2009 and 2010 at Rockford, IL (RFD).

13. Improvements have been made to the analysis technique including: interpolation of rawinsonde soundings, adjusting distance criteria for WVSS-II data filtering to take account of moisture advection and adding wind observation variability limits to the statistical analysis process to provide an independent standard for identifying periods of low and high natural atmospheric variability.

14. The most recent comparison analysis results suggest that:

- The WVSS-II-v3 systems appear to meet WMO observing requirements across all specific humidity ranges in both ascent and descent.
- The engineering changes made to the WVSS-II since 2008 seem to have alleviated the problems with data taken during descent observed in earlier tests.
- Overall, the WVSS-II SH observations match the rawinsonde data very closely, with random differences ranging from 0.2 to 0.7 g/kg at all levels, well within WMO recommendations.

PLANNING AND IMPLEMENTATION OF THE AMDAR WATER VAPOR MEASUREMENT PROGRAMME

15. It is clear that the development of the WVSS-II-v3 system is reaching the stage where the AMDAR Panel can seek the sensor’s endorsement by WMO as a validated operational sensor that conforms to CIMO standards for upper air measurement of water vapor.

16. In which case, the Joint Meeting may also like to consider how best to assist operational AMDAR programmes and WMO Members to implement the AMDAR Water Vapor Measurement Programme (AWVMP).

WMO, CIMO and CBS Endorsement of WVSS-II

17. If or when the AMDAR Panel decides that the WVSS-II is suitable to be declared an operational sensor, based on the results of tests and comparisons undertaken, consideration should be given as to how best to seek the endorsement and ratification of the sensor by WMO as a suitable system for deployment by WMO Members as a component of the World Weather Watch (WWW) Programme.

18. **Recommendation 1**: The Joint Meeting to consider the following approach:

1) The Panel and ET-AIR to commission a paper that summarises the development, testing and result of the WVSS-II sensor making the case for the sensor's approval as an operational sensor and system by the Panel and by WMO;
2) Through the CIMO Theme Leaders on Aircraft Measurements, the AMDAR Panel and ET-AIR to recommend to CIMO, by reference to the paper, that:
    a. the WVSS-II sensor should be endorsed by CIMO and CBS as a candidate system for operational deployment by Members; and
    b. the technique employed by the WVSS-II sensor should be appropriately integrated into the CIMO Guide.
3) Through the CBS OPAG ICT-IOS, the AMDAR Panel and ET-AIR to recommend to CBS, by reference to the paper, that:
    a. the WVSS-II sensor should be endorsed by CBS as a candidate system for operational deployment by Members; and
    b. the technique employed by the WVSS-II sensor should be appropriately integrated into CBS relevant Manuals and Guides.

19. **Recommendation 2**: In addition to the formal ratification of the measurement technique by WMO, the Panel might consider the compilation of a formal Statement of Support for the implementation of AMDAR water vapor measurement into operational practice in the GOS, initially to be made by the Panel and ET-AIR with the aim of seeking its endorsement by CBS and CIMO Commissions and eventually by the Executive Council and/or WMO Congress. An example draft that might form the basis of such a Statement of Support is submitted in Appendix 2.

AMDAR Programme Planning and Implementation of AMDAR Water Vapor Measurement

20. As documented in Appendix 1, the AMDAR Panel had previously considered an international approach to the implementation of AWVM and had commenced planning in cooperation with the manufacturer to this end.

21. The advantages of such an approach are considered to be the following:

- A consolidated international project-based approach to AWVM development will present a solid, unified and convincing interface to both the manufacturer and the aviation community;
- Allows a unified planning approach to more complex planning logistics and aspects such as sensor certification and their international extension, stream-lining and standardisation of installation and maintenance processes, etc;

- May offer the opportunity to work with the manufacturer to reduce purchase costs;
- May allow the manufacturer to better plan for sensor manufacturing; and,
- Allows a uniform approach to business cases and justifications for airlines and NMHSs.

22. **Recommendation 3**: The Joint Meeting to discuss the merits of re-instating an international approach to the further development of AWVM activities through a project coordinated by the AMDAR Panel, CBS and CIMO.

23. **Recommendation 4**: If recommendation 3 is adopted, the Joint Meeting to consider the following issues and aspects in relation to a project-based approach to AWVM implementation:

1) How to ensure that Panel and ET-AIR maintains and is seen to maintain appropriate impartiality with corporate entities;
2) How to approach the manufacturer to seek their cooperation;
3) How to approach Members to seek their participation in the project;
4) How to approach Airlines and the Aviation Industry to seek their participation in the project;
5) The compilation of a business case for NMHSs;
6) The compilation of a business case for Airlines;
7) Further study and projects in support of the project including:
    a. Icing potential and icing alerting;
    b. Impact and use of water vapor data for aircraft operations, and,
    c. Impact of (improved) water vapor data in climate studies.

24. **Recommendation 5**: If recommendation 3 is adopted, the Joint Meeting to consider the development of an Implementation Plan for the AWVM project.

APPENDIX 1

AMDAR Water Vapour Sensor Development History to 2009

Background

WVSS-II - Water Vapour Sensing System Mark II

- Introduction of a viable water vapour sensing system to AMDAR measurement systems has been considered the Holy Grail in this area since the program's inception (late 1980s).
- The WVSS-II sensor utilising a laser diode, I/Io, direct sensing technique has long been thought to hold the most promise to provide a suitable level of resolution and uncertainty for climate applications across the tropospheric water vapour range.
- Water vapour measurement capability for AMDAR will open up the possibility for large scale resource and infrastructure reconfiguration of the upper air measurement system, particularly the radiosonde network.
- The Water Vapour Sensing System Mark I (WVSSI) system first trialled utilised a thin-film capacitor sensor (similar to a radiosonde humidity sensor) but these sensors deteriorated quickly with operational use and proved to be non-viable as a solution.
- The history of the development of the WVSS-II sensor development by SpectraSensors Inc, USA is provided in detail below.
- WVSS-II (Version 3) specifications are available from the SSI website at: http://www.spectrasensors.com/wvss/

WMO Panel WVSS-II Project

- Seeing the potential of the WVSS-II sensor, the AMDAR Panel has closely followed the development process underway in the USA and had significant input into the design and processing specifications.
- In January 2004, the Panel TC contacted Members regarding the possibility of involvement in the trial of WVSS-II sensors onboard AMDAR aircraft.
- By December 2004, the Panel had initiated a plan in cooperation with SpectraSensors Inc (SSI) involving:
    - Panel member agencies undertaking the purchase and installation of 10 or more WVSS-II sensors (@ US$15K each) on Airbus A320 aircraft installed on the Airbus factory line:
    - Germany, Lufthansa: 3 sensors;
    - Australia, Jetstar: 1 or 2 sensors;
    - France, Air France: 5 sensors;
    - New Zealand: 1 sensor.
    - SSI working with Airbus to facilitate the integration of the sensor;
    - Lufthansa obtaining an STC for A320 in Germany;
    - SpectraSensors undertaking to finance and manage the testing and administrative costs of obtaining an STC for the A319/A320 family in USA, Australia, New Zealand and Sth Africa;
    - Deadline for purchase: May 2006
- By June 2005, reports of critical issues with the data quality from the sensors on the UPS fleet had begun to emerge and the planning for the Panel project did not move any further forward.
- At December 2005, the deadline for sensor purchase was extended by SSI to December 2006 to coincide with completion of the re-trial and comparison being undertaken in the USA in late

2006. At this time, the Panel was not aware of the full extent of the re-engineering issues associated with WVSS-II-V1.

- Throughout this time, DWD had elected to go ahead and purchase and trial 3 sensors with Lufthansa in fulfilling the obligation to obtain the STC for Lufthansa A319.
- By December 2006, issues with WVSS-II-V2 had begun to emerge and the Panel TC obtained an extension of the sensor purchase to July 2007.
- In July 2007, SSI advised the Panel TC that SSI was undertaking laboratory testing of returned WVSS-II-V2 sensors and the deadline purchase date was again extended to November 2007.
- By February 2008 it was clear that the project was in jeopardy and that, once again a major redesign would have to be undertaken by SSI.
- In December 2008 the Panel Chairman advised that, in July 2008, SSI had updated their offer to the Panel for purchase of 10 sensors at a reduced cost as referenced below [8].
- The offer represented a unit cost of ~US12K. The Panel Chairman invited interested members to write letters to SSI indicating an expression of interest.

Summary of Sensor Issues

- WVSS-I (thin-film capacitor system): 3-6 month degradation due to aging effects.
- WVSS-II-V1:
  1) Non-ambient moisture trapped in the laser sample field of view caused an average +2 g/kg wet bias in almost measurements. This bias is very pronounced above 500 hPa;
  2) Dry bias observed during descent when the sensor intake encountered dew points higher than the temperature of the intake hose surface temperature. This condition caused condensation within the intake hose reducing the moisture sampled by the sensor during aircraft descent;
  3) precision of the observations from the WVSS-II sensor, as encoded mixing ratio observations within the B-757 DFDU avionic software, was clipping the mixing ratio values to two digits. This caused mixing ratio above 10 g/kg to be encoded to only one decimal place. [1]

- WVSS-II-V2 (Engineering changes, eliminate trapped moisture by: a) improved laser seal; b) additional desiccant; c) heated intake tube.):
  1) a dry bias that was manifest in 10 units;
  2) a small wet bias was exhibited in 2 units during en route flight segments;
  3) a lack of sensitivity to atmospheric conditions was evident in 7 units; and
  4) failure to operate upon initial installation.
- Of the 19 WVSS-II.2 units installed, only 4 units have consistently performed within minimum operating standards. [1]
- WVSS-II-V3 Engineering improvements:
  1) Improved Signal Processor and Laser Driver Component Quality
  2) Improved characterization of pressure/temperature calibration mapping
  3) Improved quality control/testing and rigorous laser and SEB burn-in regime (22 days)
  4) Added Laser and Component Thermal Isolation
  5) Re-design of the gas chamber thermistor
  6) Addition of a SEB external test connection
  7) Improved laser seals
  8) Improved laser seal test protocols, including N2 leak test and final 5 psi over pressure of laser chamber using He gas.

Summary of Test Results

WVSS-II-V1

- From: June 2005 WVSS-II – Rawinsonde Intercomparison Study, Petersen, Feltz, Bedka, University of Wisconsin – Madison, August 2006 [2].

WVSS-II-V2

- See: Results of the November 2006 WVSS-II – Rawinsonde Intercomparison Study, Petersen, Feltz, Bedka, Olson, University of Wisconsin – Madison, March 2008 [3].
- From: The E-AMDAR Humidity Trial (2006-2009), Deutscher Wetterdienst (DWD), Axel Hoff, October 2009 [7]:
    - The WVSS-II version of late 2005 was tested...in the environmental simulation chamber at the FZJ (Smit & Sträter, 2006). Pressure, temperature and frost point temperature were varied in the same fashion as they are typically observed during aircraft flights between surface and up to 12 km altitude. WVSS-II tracks humidity structures very well at water vapour mixing ratios between 100 and 20,000 ppmv. At these moderate humidity levels typical for the lower and middle troposphere the performance is good with relative accuracy of ± (5 to 10) %. However, particularly at upper tropospheric conditions where water vapour mixing ratios are well below 100 ppmv the accuracy of WVSS-II declined rapidly down to the detection limit of about 70 ppmv.
    - Several sensors of a batch of WVSS-II units delivered to the DWD in 2006 where subject of a climate chamber test at FELG...
    - Summary of both tests:
        - Difference to standard: +/-10% (cf specification +/-5%)
        - Lower detection limit: 0.04 g/kg or 70 PPMV (cf specification 0.025 g/kg or 40 PPMV)
    - Comments:
        - The accuracy is slightly worse compared to that of standard;
        - The sensor has a usable range in the mid latitudes atmosphere reaching from ground to about 300 hPa in summer and to about 500 hPa in winter.

WVSS-II-V3

- From: WVSS-II Assessment at the DWD Deutscher Wetterdienst / German Meteorological Service Climate Chamber of the Meteorological Observatory Lindenberg, Axel Hoff, September 2009 [5]:
    - Test Conditions:
        - Comparison with MBW 373LX chilled mirror and Central Aerological Observatory TOROS chilled mirror
        - 1 WVSS unit
        - Pressure: 1050 to 800 and 200 to 700 hPa
        - Temperature + 23ºto - 54ºC
        - Dewpoint +20 to -75º
        - Sample Gas flow rate 1 l/min
        - Concentration range from ~ 0.01 to 10 grams/kg
    - Results:
        - In the range of 1 to 10 g/kg there appears to be a tendency to a dry bias of 5 to 7%;
        - Below 0.5 g/kg, uncertainty is of the order of ±10%; however:

        - The references used, particularly at low humidity values, have a similar uncertainty of ±10%.
    - Issues:
        - Flow-rate too low to properly simulate flight conditions.
- From: Retest and Evaluation Report, US Department of Commerce, US Department of Commerce [9]
    - Repeat of earlier work with improved test system which had improved measurement uncertainty.
    - Test Conditions:
        - Thunder Scientific 4500 used to generate known temperature, humidity and pressure. Verified using RHS373 chilled mirror.
        - WV range 60-22000PPMv tested, pressure 200-1030hPa, 4-6l/min.
        - Temperature not regulated.
    - Results:
        - Within +/- 5% for pressure > 250hPa for all conditions. Significant errors (up to 20%) at pressure<200hPa and flow rates different from 5l/min
        - WVSS-II sensor shows larger noise/variation in values with time than the other sensors (with up to 10x the standard deviation at lower pressures), and "took a long time to stabilize when exposed to constant humidity, ... especially at four and six liters per minute flow rates".
- From: WVSS Annual Review #3, ARINC, NOAA-NWS, November 2009 [6]:
    - Test Conditions 1:
        - Comparison with Licor chilled mirror
        - WV range 50 to ~30000 PPMV
        - 2 WVSS-V3 units
        - atmospheric pressure
        - Results:
            - Within +/-5% over operational range (> 50 PPMV)
        - Issues
            - Difference increases at low PPMV due to SNR issues at low concentration
    - ? Test Conditions 2:
        - Use of Thunder Scientific 4500
        - WV Range: 50 to ~22000 PPMV
        - Pressure: 200 to 1030 hPa
        - Results:
            - Within +/-5%
        - Issues:
            - Require clarification on comparison standard used.
- From: Initial Early-Look Assessment of WVSS-II vs. Rawindsone Inter-comparisons during April- May 2010 at Rockford Il, Petersen, Feltz, Olson, University of Wisconsin-Madison, 2010.[10]
    - Test Conditions:
        - Comparison with Rawinsonde data for evening flights from 27th April - 7th May 2010.
        - Ascent and Descent data used.
        - Direct comparison with closest Rawinsonde report (rather than interpolation between bounding data).
    - Results
        - Good agreement between the different WVSS-II sensors on a range of planes and consistent behaviour between runs from the same plane on different days.

        - Relative Humidity shows a slight positive bias, and Standard Deviation/random error of as much as 15% across the comparison, particularly at upper atmosphere regions (which are both likely to be more variable, and taken at greater ranges from the airport/Rawinsonde location).
        - When comparison conditions are tightened ("Restricted Comparison
        - Conditions") to <7% time and <10% height, then bias largely disappears and random error reduces to about 5% (although with a general trend of increasing error with height (and distance))
        - Under the "Restricted Comparison Conditions", temperature shows about 0.5-1 degree warm bias, and a similar random error. Using the Rawinsonde temperatures in the RH calculations, rather than the WVSS-II temperatures (to try to separate the error in one WVSS-II system from another) did not improve the RH results particularly.
        - Under the "Restricted Comparison Conditions", specific humidity showed bias and random error of 0.2-0.5g/kg (which is apparently "well within WMO standards for both global and mesoscale applications").
        - In all, conclusions are promising but warrant more analysis
- From: Monitoring of 3 E-AMDAR humidity seonsors WVSS-II onboard Lufthansa aircraft, Stefan Klink, Offenbach, February 2010 [11]
    - Test Conditions
        - 3 WVSS-II sensors (built in 2006) were flown on Lufthansa aircraft from June 2007-January 2010.
        - Comparison to DWD (German Weather Service) numerical weather model, COSMOEU, which covers all Europe
        - Average value for (model)-(observation) plotted for each day for mixing ratio, temperature (for comparison) and relative humidity.
    - Results
        - All 3 sensors show a dry bias [-0.45g/kg, -0.93g/kg, -0.73g/kg].
        - Show a seasonal variation (summer vs winter) to model, although some discussion as to whether the variation is in the sensor or in the comparison model.
    - Issues
        - Artifacts in data (eg. EU4593 shows a slow development of a dry bias (to -4g/kg) which then "clears up" over a couple of days)
        - Intermittent data outages (unknown if sensor or data network as happens for temperature as well as humidity related measurments).

Sensor Development and Test History

Summary

- 1997-2002: United Parcel Service B-757 aircraft (intially 6 growing to 30) equipped with WVSSI (thin-film capacitor sensing system).
- 2004: Rex Fleming documents 3-6 month timeframe for degradation of WVSSI TFC sensor.
- 2003: WVSS-II-V1 (Tunable Diode Laser system - TDL) prototype tested on NOAA P-3 research aircraft against chilled mirror.
- 2005: 25 WVSS-II-V1 sensors installed on United Parcel Service B-757 replacing WVSSI senors.
- 2006: Petersen et al [2] analysis of June 2005 field assessment comparison with co-located radiosonde systems identifies systematic biases for most sensors and overall wet bias.

- October to November 2006: WVSS-II-V2 (Engineering changes, eliminate trapped moisture by: a) improved laser seal; b) additional dessicant; c) heated intake tube.) implemented on UPS aircraft (19 of 25).
- November 2006: Rawinsonde Intercomprison Trial conducted for comparison of UPS WVSS-II-V2 with co-located radiosonde.
- November 2006: Cessation of rollout of WVSS-II-V2 due to "increasing concerns over observation accuracy".
- January 2007: Lufthansa commences operations with a WVSS-II-V2 sensor onboard an A319. Data from this aircraft became available on the GTS in June 2007.
- June 2007: NOAA awards contract to ARINC with sub-contracts SSI (SpectraSensors Inc) and South West Airlines (SWA) to:
    - manufacture 56 WVSS-II.V3 units;
    - install 31 units on SWA B737-300 aircraft;
    - replace 25 WVSS-II.V2 units with WVSS-II.V3 units on UPS B757 aricraft;
    - provide all aircraft integration documentation (e.g. STC - Special Type Certification);
    - obtain STC for B737-300 aircraft;
    - obtain amended STC for B757 aircraft.
- August 2007: 4 WVSS-II-V2 units returned to SSI for comprehensive chamber testing and incremental re-engineering to overcome a thermal sensitivity issue causing thermal lag which results in sensor bias.
- March 2008: Petersen et al provide results on 2006 Rawinsonde Intercomparison Study (WVSS-IIV2) [3].
- May 2008: SSI completed final updates to the WVSS-II-V3 design.
- May - June 2009: DWD Chamber testing of WVSS-II-V3 at Lindenburg
- June 2008: SSI conducted a pilot production run constructing 15 WVSS-II-V3 units.
- June 2008: Status Report of the USA AMDAR Programme [4]: Chamber testing of WVSS-II-V3 commenced at NOAA Upper-Air test Facility in Sterling, Virginia.
- September 2009: Status Report of the USA AMDAR Programme [4]: Chamber testing of the WVSS-IIv3 completed by the Deutscher Wetterdienst, Climate Chamber of the Meteorological Observatory, Lindenberg, Germany [5].
- November 2009: Status Report of the USA AMDAR Programme [4]: 14 of 25 WVSS-II-V3 implemented on UPS B757.

Detailed History of Sensor Development in the USA by SpectraSensors

- *The U.S. has been investigating strategies for installing water vapor sensors on commercial aircraft since 1993, when the Federal Aviation Administration (FAA) established the Commercial Aviation Sensing Humidity (CASH) program. The CASH program was essential in development of sensor specifications leading to an operational deployment of a Water Vapor Sensing System (WVSS) I (Fleming, 1996). [1]*
- *A demonstration system based on the B. F. Goodrich Rosemount Aerospace, Inc., thin-film capacitor was deployed and operated on United Parcel Service B-757 aircraft from 1997 through 2002. Initially the WVSS I demonstration fleet was limited to 6 aircraft, but eventually grew to 30 aircraft by 2001. [1]*
- *While initial sensor accuracy was similar to radiosonde humidity observations (Fleming 2000) early on in the demonstration, aging effects on the thin-film capacitor (TFC) caused the sensor sensitivity to be steadily diminished resulting in a significant dry bias after 3-6 months operation (Fleming 2004). [1]*
- *One of the lessons of the WVSS I demonstration was that the water vapor sensor must be accurate and stable for a longer time duration than the maintenance cycle interval of the aircraft they are installed on, which is generally a 30 month period. Otherwise, air carrier will be unable to service the sensor should it fail in the interim period. Alternatively, this type of sensor*

needs to be engineered to allow easy access by aircraft maintenance crews for efficient swap-out of degraded TFC sensors. Unfortunately, the WVSS I did not have a design that allowed quick TFC swap-out. [1]

- *Resources for the development of WVSS II sensor was provided through a UCAR contract to SpectraSensors (SSI) for sensor development and United Parcel Service (UPS) for aircraft sensor integration labor. The chosen technical solution to avoid loss of sensor sensitivity was to utlize laser technology. [1]*
- *Using a 1.37 micron telecommunications grade Tunable Diode Laser (TDL), the WVSS II directly measure mixing ratio rather than relative humidity by measuring the absorption of light within a 24 cm path length sample. [1]*
- *The WVSS II prototype was tested on the NOAA P-3 research aircraft in 2003 against a chilled mirror test instrument. Test results from a variety of atmospheric conditions, including Hurricane Isabel, showed good agreement between the two sensors. [1]*
- *After obtaining the appropriate FAA Supplemental Type Certificate (STC) for operating the WVSS II on the B-757, the WVSS II was mounted in the same location as the WVSS I installation as a sensor "swap". [1]*
- *Between February and June 2005, 25 WVSS II, version 1, (henceforth WVSS-II.1) sensors were installed on UPS B-757 aircraft. The WVSS II.1 sensors operated from spring 2005 through fall 2006, during which time their data were assessed using a variety of approaches including a June 2005 field assessment (Petersen 2006a).These assessments identified a systematic bias associated with most of the sensor observations, including an overall wet bias particularly evident during the en route phase of flight and a dry bias that was manifest during the descent phase of flight. [1]*
- *Engineering changes to the WVSS II.1 sensor were developed to eliminate trapped moisture in the sample chamber and to avoid condensation by improving the laser seal and adding additional desiccant and by using a heated intake hose which will keep the hose warmer than the dew point of the air sampled. The precision limitation within the aircraft avionics is being improved by using implementing a base 40 compression algorithm supporting the full range of possible atmospheric mixing ratios to three significant digits. These engineering and software changes were implemented in November 2006 and validated through a second AERIBAGO field assessment conducted 1-2 weeks after the WVSS-II.2 sensor installation (November 2006). [1]*
- *...the first look at the WVSS-II.2 sensor performance data as compared to November 2006 field assessment data by the CIMSS researchers (Petersen, 2008) found the following "when contrasted with results obtained from the Spring 2005 assessment, it appears that the engineering changes made after the 2005 test were at least partially successful in removing error in data taken during ascent. First, the positive Biases that were present above 850 hPa in the 2005 data sets have been essentially eliminated. In addition, the unexplained bimodal character of 'systematic' error (negative Biases below 850 hPa and positive above) has been eliminated". Thus as problems identified in the WVSS-II.1 sensor were resolved by engineering changes made for WVSS-II.2. [1]*
- *However, these corrective changes provided a window on new and different problems were revealed in the sensor performance. The WVSS-II.2 problems were categorized into four failure modes: 1) a dry bias that was manifest in 10 units, 2) a small wet bias was exhibited in 2 units during en route flight segments, 3) a lack of sensitivity to atmospheric conditions was evident in 7 units, and 4) failure to operate upon initial installation. Of the 19 WVSS-II.2 units installed, only 4 units have consistently performed within minimum operating standards. [1]*
- *...WVSS-II.3 development and operation are funded through a contract from NOAA National Weather Service. This contract, awarded in June 2007, has ARINC serving as contract lead, and SSI and Southwest Airlines (SWA) serving as sub-contractors to ARINC. This contract specifies ARINC, SSI, and SWA build 56 WVSS-II.3 units, and install these sensors on 31 SWA B737-300 aircraft, and replace 25 WVSS-II (versions 1 and 2) units currently flying on 25*

UPS B757 aircraft, with 4 spare units available. The 60 WVSS-II.3 sensors are to be produced and installed within 18 months of the start of the contract, or by December 2008. All necessary aircraft integration documentation (e.g. Special Type Certification (STC)) is covered by the contract, including obtaining an STC for the SWA B737-300 aircraft and an amended STC of the UPS B757 aircraft. [1]

- *With the assistance of United Parcel Service (UPS), 4 of the 19 WVSS-II.2 units flown on B-757 aircraft since November 2006 were returned to SSI in August 2007. SSI used these units as the basis of validating their preliminary analysis of the sources of system component failures through chamber testing, and by re-testing the units after incremental system component updates scheduled for introduction into the WVSS-II.3 were retrofitted into the returned WVSS-II.2 units. Factory testing of the unmodified returned WVSS-II.2 units showed the units exhibited a wet bias, with all four units demonstrating a large thermal sensitivity, specifically showing thermal lag (e.g. warmer than actual during ascent, and cooler than actual during descent as compared with a chilled mirror). Also determined during the tests, the thermistor in the sample chamber was not detecting the gas temperature, but rather the sample cell wall temperature. [1]*
- *The following engineering changes were implemented in the WVSS-II.3 sensor as a result of the testing of WVSS-II.2 sensors:*
    1) *Improved Signal Processor and Laser Driver Component Quality*
        a. *Use of MILSPEC resistors: from 1% to 0.1% tolerance*
        b. *Use of MILSPEC capacitors: from 5% to 1% tolerance*
        c. *Temperature Coefficient: from 600-800 PPM/oC to 30 PPM/oC*
    2) *2. Improved characterization of pressure/temperature calibration mapping*
    3) *3. Improved quality control/testing and rigorous laser and SEB burn-in regime was implemented (22 days)*
    4) *Added Laser and Component Thermal Isolation*
        a. *Isolate the Sensor Equipment Box (SEB) from the aircraft skin*
        b. *Isolate laser head from the sample cell*
        c. *Isolate the gas temperature sensor from the cell wall*
    5) *Re-design of the gas chamber thermistor*
    6) *Addition of a SEB external test connection*
    7) *Improved laser seals:*
        a. *Improved milling and geometry of O-ring seal*
        b. *Added hermetic connectors*
        c. *Added "pinch tube" design for improved seal integrity*
    8) *Improved laser seal test protocols, including N2 leak test and final 5 psi over pressure of laser chamber using He gas. [1]*
- *When these engineering changes were introduced into the WVSS-II.2 units returned from UPS, test results from varying the ambient temperature from -5C to +30C show a decrease in thermal dependency from a range of +/-50% temperature induced error decreased to +/-5%. [1]*
- *SSI completed final updates to the WVSS-II.3 design in May 2008, and conducted a pilot production run constructing 15 WVSS-II.3 sensors in June 2008. [1]*

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APPENDIX 2

DRAFT WMO AMDAR PANEL STATEMENT OF SUPPORT FOR WATER VAPOR MEASUREMENT FROM COMMERCIAL AIRCRAFT AS A COMPONENT OF THE AMDAR PROGRAMME

The World Meteorological Organization (WMO) and its National Meteorological and Hydrological Services (NMHS) member constituents have always recognized the cooperation received and the collaboration undertaken with both commercial and government organizations and entities in carrying out its mandated role as the United Nations authority on weather, climate and the water cycle.

The Aircraft Meteorological Data Relay (AMDAR) Programme, which has been a meteorological observations component of the WMO World Weather Watch Programme for around thirty years, is one such cooperative programme that greatly depends upon partnerships between national and international aviation and meteorological communities and organizations.

The Global AMDAR Programme currently delivers over two hundred thousand automated reports of critical meteorological variables per day that are derived from the innate instrumentation onboard commercial jet aircraft platforms.

The benefits of the AMDAR Programme through the delivery of high quality and relatively-low cost upper air measurements of air temperature and wind speed and direction have now been well established and documented within the scientific literature. The significant and positive impact the data products of the AMDAR Programme have on areas such as aviation and public weather forecasting, numerical weather prediction and climate monitoring are also well understood and appreciated by meteorological data users, researchers and forecasters.

In recent years, in the wake of the successful and dramatic expansion of the Global AMDAR Programme and the demonstration of the significant benefits of the AMDAR Programme to meteorological Data Users and Application Areas, the AMDAR Programme has been declared an operational component of the WMO World Weather Watch Upper Air Programme.

Therefore, it is vital that the AMDAR Programme continues to be supported and enhanced by all aviation and meteorological partners that participate in the Programme or have the potential to do so.

Alongside the growth of the AMDAR Programme, the scientific and research community has been endeavouring to develop a sensing technology that would provide an additional vital component to the AMDAR Programme; that being the measurement of water vapor from aircraft platforms.

Water, in its gaseous, liquid and solid state is one of many constituents of the earth’s atmosphere; however, in terms of its contribution to the energy balance and budget of the atmosphere and therefore its contribution to both climate and weather, it is one of the most important. The primary reason for this is that water vapor plays two key roles in the earth-atmosphere system’s energy cycles.

Firstly, by virtue of its properties of state and its thermal properties, water in the atmosphere is one of the most significant parameters in all weather-related phenomena over all temporal and spatial scales in which atmospheric energy is transferred, stored and released. Secondly, water is a strong Greenhouse Gas, which means that it absorbs the earth’s outgoing radiation at the molecular level, thereby significantly contributing to the regulation of the temperature of the earth-atmosphere system.

For this reason, accurate measurement and modeling of water vapor and water-related processes in the atmosphere are essential in the detection and forecasting of those severe weather events that most affect aviation operations. Therefore, the impact of more widely and more frequently measuring water vapor is expected by meteorologists to be highly significant in improving modeling and forecasting skills across all meteorological application areas.

At the 14th Session of the WMO Commission for Basic Systems, The Vision for the Global Observing System in 2025 was approved and contained the following statements in relation to aircraft observations:

Aircraft observing systems:

- Will be available from most airport locations, in all regions of the world;
- Flight-level and ascent/descent data will be available at user-selected temporal resolution;
- Will observe humidity and some components of atmospheric composition, in addition to temperature, pressure and wind;
- Will also be developed for smaller, regional aircraft with flight levels in the mid-troposphere and providing ascent/descent profiles into additional airports.

Whilst the sensors and systems that enable measurement of air temperature and wind are generally innate to commercial jet aircraft, thus allowing the implementation of the AMDAR Programme via a software deployment only, the development of a water vapor measurement capability for the AMDAR Programme will require the deployment of a suitable sensor and its integration into the aircraft body and avionics infrastructure.

In cooperation with manufacturers, airline partners and scientific laboratories, such sensors have been developed, deployed, tested and refined and have been shown to now meet WMO requirements for operational performance and standards for water vapor measurement accuracy.

WMO recommends, encourages and supports NMHS and Airline partners in the AMDAR Programme in their endeavors to implement a water vapor measurement capability on commercial aircraft platforms operationally and expects that such an enhancement to the AMDAR Programme and, as a result, the World Weather Watch Programme, will deliver significant benefits to both the aviation and meteorological communities.