1.0 WVSS-II, Water Vapor Sensing System, Version Two

This paper briefly describes the Water Vapor Sensing System version two, WVSS-II, how it works, how the information is transmitted and used, and why it is important to weather forecasting operations. For those readers not familiar with aircraft meteorological observations through AMDAR or MDCRS, it may be helpful to first review some of the acronyms, agencies, companies, and systems commonly used by these systems, provided in section 5.0. For those readers interested in additional technical information on WVSS-II, references to independent external publications are found in the WVSS-II Technical Publications Listing on our website.

1.1 Introduction to WVSS-II

The Water Vapor Sensing System, WVSS-II, is a unique sensor technology developed to accurately measure atmospheric water vapor from airborne platforms. WVSS-II was developed by SpectraSensors, Inc. under sponsorship by the U.S. National Weather Service, NWS, through prime contractor ARINC. It is designed to be mounted on commercial aircraft in support of the global Aircraft Meteorological Data Relay program, AMDAR, implementyed by national meteorological and Hydrological Service, NMHS, as coordinated by the World Meteorological Organization, WMO. The system utilizes Tunable Diode Laser Absorption Spectroscopy, TDLAS, technology to accurately measure the amount of atmospheric water vapor in a sample of air continuously drawn from outside the aircraft. This data is coupled with meteorological wind and temperature data collected by the aircraft, and transmitted to the NMHS for use in all facets of forecast operations. The ability to accurately forecast future weather phenomenon begins with observing the upper air conditions at sufficient observation density and timing to represent the current state of the atmosphere, using a variety of observation methods. The AMDAR program has proven to be one of the most cost effective methods to gather a large volume of high quality upper air observation data.

1.2 The WVSS-II System Description

WVSS-II is designed to be mounted on commercial or research aircraft of any size or manufacturer, to provide a direct measurement of atmospheric water vapor as the aircraft flies its normal route. The TDLAS technology used in WVSS-II was initially developed by NASA JPL, for use on space mission platforms. The aircraft utilizes real-time data transmission systems to transmit this data to the respective AMDAR systems including the U.S. contribution to AMDAR, the MDCRS program. WVSS-II meets the demanding aviation industry operational requirements with low weight, low drag, low size, low power, low maintenance, and high reliability, and no consumable components. The WVSS-II consists of three main parts, the external Air Sampler, connecting hoses, and the analyzer System Electronics Box (SEB), as seen in Figure 1.
The UCAR designed and patented external Air Sampler\(^1\) is mounted on the outer skin of the aircraft to continuously collect air through a low profile, low drag inlet port. The WVSS-II Air Sampler is specifically designed to minimize the impact externally mounted components may have on flight operations. The Air Sampler has proven to be effective in collecting a representative air sample for the measurement of atmospheric water vapor.

The input air continuously flows from the Air Sampler through the aviation certified connecting hose into the SEB analyzer for measurement. Precautions are taken to prevent condensation as the aircraft transitions from very cold air at higher altitudes, to warmer and higher humidity air at lower altitudes. After the air passes through the measurement cell inside the SEB, it is expelled through the outlet hose to the outlet port of the Air Sampler.

The analyzer measurement cell inside the SEB uses the SpectraSensors implementation of Tunable Diode Laser Absorption Spectroscopy to accurately measure the amount of water vapor in the atmosphere. While the details of the patented SSI implementation are proprietary, we can summarize here. The laser is specifically selected to be at a wavelength corresponding to the absorption wavelength of water. Therefore the absorption of the laser light is proportional to the amount of water in the sampled air, and can be measured by the detector in the analyzer. Adjustments are made for the effects of changing air pressures and temperatures. The resulting measurement of water vapor is provided as Mixing Ratio with accuracy and stability suitable for operational use in all meteorological forecast applications.

### 2.0 How the WVSS-II Data is Collected from the Aircraft

The real-time collection of water vapor data from WVSS-II equipped aircraft data is a complex system requiring multiple steps in the process. The WVSS-II data output from the SEB is connected to the aircraft computers for on-board processing. There it is combined with other AMDAR/MDCRS meteorological data and flight condition information and formatted into downlink messages according to the ARINC standards for the Aircraft Communication Addressing and Reporting System (ACARS). The ACARS communications are independently provided by either of the two ACARS providers, ARINC or SITA. ACARS messages are then transmitted by the datalink to ground stations positioned around the world and then passed to

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\(^1\) The Aerial Sampler Patents, U.S. Patent No.s 6,809,648 and 6,997,050, were developed by the University Corporation for Atmospheric Research. The University Corporation for Atmospheric Research Foundation has licensed the Aerial Sampler Technology to SpectraSensors Inc.
the appropriate facility for processing. The meteorological data, including water vapor data, are converted to WMO standard BUFR format and routed to the appropriate National Meteorological and Hydrological Service, NMHS, for use in forecast operations as well as to the airline operations. Figure 2 depicts the end-to-end processing for WVSS-II and other meteorological data in the U.S. MDCRS program. Other international implementations have a similar process flow, with various organizations doing the communications, ground processing, quality control, and other functions.

Figure 2 - End-to-End Flow of Data within the U.S. MDCRS Program

All of these data are functionally equivalent to data derived from traditional radiosonde weather balloon observations. Today such traditional methods of measuring humidity only provide samples from a few locations, typically twice per day, according to international convention. With the use of multiple WVSS-II installations, a much more frequent sampling of the moisture in our dynamic atmosphere can be achieved with much greater density of observation. And this improvement in observation quality and quantity is achieved at a much lower cost per observation, than with traditional methods. This improvement in input data results in improved forecast output products to better support the aviation community as well as all users of products from meteorological services.

Today the AMDAR system receives over 400,000 measurement points a day for wind and temperature from several thousand aircraft participating in the program. These data are available for input to weather forecast models, which are updated typically every three or six hours. Prior to WVSS-II, the water vapor data was not available from AMDAR. Therefore the weather forecast models would only be able to use water vapor data provided every 12 hours through weather balloon launches at approximately 70 sites scattered throughout the continental U.S. and 350 sites globally. So forecast models have been forced to use data as much as 12 hours old. In 12 hours, the atmosphere can change quite dramatically, which leads to inaccuracies in forecast model outputs. Once the network of WVSS-II equipped aircraft is fully deployed, the water vapor data from aircraft can also be updated at times more consistent
with the forecast models. The resulting benefit to meteorological forecasting computer models is expected to be significant, and provide direct benefit to the aviation community as well as improve the forecasts we all depend on daily.

3.0 Why is Water Vapor Measurement So Important

The primary measurements from the upper atmosphere used in accurate weather forecast modeling include observations of temperature, wind speed, wind direction, and humidity or water vapor. The measurement of water vapor in the atmosphere is very important as it is one of the primary reasons severe weather is created in sudden, hard to predict storms. It is the water vapor that condenses into clouds that grow into destructive storms and other meteorological phenomenon. These storms play havoc on our population as well as causing unexpected delays in air travel and unplanned aircraft rerouting to maintain aviation safety. Being one of the primary atmospheric parameters, an improved understanding of atmospheric water vapor will improve the forecast of precipitation, thunderstorms, fog, winter storms, ceiling visibility, and turbulence. The Federal Aviation Administration has consistently stated that unexpected severe storms cost the aviation industry well over a billion dollars a year. The broader impacts to society are much greater.

Water vapor is also the primary greenhouse gas in our atmosphere and traps heat very effectively. Because it is generally a clear gas like other greenhouse gases, it allows solar radiation to pass through it relatively undiminished on its way to earth. Once the Earth's surface re-radiates that energy in the form of heat, it is absorbed by the water vapor which in turn causes a warming effect, since the heat is not able to escape back into space. With any heating of the earth comes increased evaporation of water, increasing this effect even further. By some estimates, water vapor is responsible for two-thirds of nature’s greenhouse effect.

There is a greater amount of water vapor in the atmosphere than any other greenhouse gas. Estimates of the volume of water in the atmosphere at any one time are about 3,100 cubic miles (mi³) or 12,900 cubic kilometers (km³). But this amount does vary from place to place and over time. Water vapor can vary between trace amounts in some locations to as much as 4% of the atmosphere in others. As a comparison carbon dioxide currently constitutes approximately 0.37% of the atmosphere, although that is on the rise. The variation of atmospheric water vapor in time and space has a significant impact on our near term weather, as well as our long term climate. With this amount of water circulating in our atmosphere it is clear that a more robust collection of water vapor measurements will greatly improve weather and climate forecasting for all stakeholders.

4.0 State of the WVSS-II Network in the U.S.

As of June 2012, there are 56 WVSS-II equipped aircraft in the U.S. network, including 25 units installed on UPS 757-200 aircraft, and 31 units installed on Southwest Airlines (SWA) 737-300 aircraft. An additional 36 units are scheduled for installation in 2012 on SWA 737-700 aircraft. Figure 3 illustrates the data collected from the aircraft that were in operation within the U.S. during a 24 hour period, June 13, 2012. While there are still many areas in

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space and time that have yet to be covered, this demonstrates the growing spatial and temporal coverage that is obtained through aircraft observations with WVSS-II.

There are 12 WVSS-II units currently delivered to various organizations in Europe for use in operational and research applications. Short term plans are in place for further expansion in Europe. The Australian Bureau of Meteorology has also begun to expand their AMDAR network, starting with 3 WVSS-II units in 2012. Planning is underway for implementations at various other National Meteorological and Hydrological Services around the world.

5.0 Acronyms and Descriptions

The following descriptions will help to better understand the acronyms, agencies, companies, and systems that are used in the collection of weather observation data from weather sensors on commercial aircraft.

ACARS – Aircraft Communications Addressing and Reporting System

ACARS is a digital datalink protocol system for transmission of short, relatively simple messages between aircraft and ground stations via radio or satellite. ACARS transmits a variety of information from aircraft to ground including meteorological data. The two most common providers of ACARS communication services are ARINC and SITA.

AMDAR – Aircraft Meteorological Data Relay

AMDAR is a program initiated by the World Meteorological Organization, WMO, to collect upper air meteorological data worldwide by using weather sensors on commercial aircraft.
ARINC – Aeronautical Radio, Inc.

The company ARINC is located in Annapolis, MD, and provides a variety of aviation services such as aviation communications, program management, and other aviation related services. ARINC is the prime contractor for the U.S. NWS MDCRS program, providing the collection of aircraft meteorological data for the U.S. NWS. ARINC is also the prime contractor to the NWS for the integration of WVSS-II on U.S. based airlines participating in MDCRS. ARINC operates an independent business unit dedicated to the establishment and ongoing maintenance of aviation related industry standards of all kinds.

BUFR – Binary Universal Form for the Representation of meteorological data

BUFR is a table-driven code form of data format defined and maintained by the WMO for the transmission of meteorological data. The latest edition is BUFR 4, however BUFR 3 is still considered to be valid for operational use by National Meteorological Services.

MDCRS - Meteorological Data Collection and Reporting System

MDCRS is the U.S. Government contribution to the global AMDAR program, for the collection of meteorological observations from participating airlines by the NWS. ARINC is the prime contractor for the MDCRS program, which collects the meteorological data through the ACARS networks. This data is then properly formatted and transmitted to the NWS for use in weather forecasting as well as to the respective airline for use in operations.

NOAA/NWS - National Oceanic and Atmospheric Administration/National Weather Service

NOAA is a U.S. Government organization reporting to the Department of Commerce, and NWS is the U.S. agency responsible for the gathering weather observation data, analyzing that data, and making weather predictions. The NWS uses data from many sources in operational weather forecasting and numerical models. These sources include ground stations, weather balloons, weather satellites, weather radars, and weather sensors on commercial aircraft. The NWS, like other National Meteorological and Hydrological Services world wide, is a member of the WMO and participates in the AMDAR program to improve the collection of upper air observations through partnership with participating airlines.

NMHS

National Meteorological and Hydrological Services are the national Government services of each nation which provide meteorological and hydrological observation and forecast support to their public. Specific organizational structures and organization names may differ from nation to nation. NMHSs are typically members of the WMO, and closely collaborate with other NMHSs on their respective scientific matters.

SpectraSensors, Inc.

SpectraSensors, Inc., the manufacturer of WVSS-II, was incorporated in 1999, as a technology spin-off of the NASA/Caltech Jet Propulsion Laboratory (JPL) in Pasadena, CA. SpectraSensors is headquartered in Houston, TX, with Engineering and Manufacturing performed in Rancho Cucamonga, CA, outside Los Angeles, and Program Management of Atmospheric Programs conducted from Bethesda, MD, near Washington DC. In June of 2012, SpectraSensors was acquired by Endress+Hauser, a large privately held sensor company operating throughout the globe. SpectraSensors operates independently and maintains all direct management and production in the U.S.
UCAR – University Corporation for Atmospheric Research

UCAR, headquartered in Boulder, CO, is a nonprofit consortium of North American member universities, which grant degrees in atmospheric and related sciences, plus international affiliates offering comparable degrees. UCAR has developed and patented the Aerial Sampler used in WVSS-II, under U.S. Patent No.s 6,809,648 and 6,997,050. The University Corporation for Atmospheric Research Foundation has licensed the Aerial Sampler Technology to SpectraSensors Inc.

WMO – World Meteorological Organization

WMO is a specialized agency of the United Nations. It is the UN system's authoritative voice on the state and behavior of the Earth's atmosphere, its interaction with the oceans, the climate it produces and the resulting distribution of water resources. WMO has a membership of 189 Member States and Territories. WMO organizes the global AMDAR program, for the collection of meteorological data from commercial aircraft.