A Conceptual Plan for a National Implementation of a Commercial Aircraft Water Vapor Sensing System

Report

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Acknowledgments

FAA's Aviation Weather Research Program and NOAA's Office of Global Programs supported this work. The basis for the number of commercial aircraft with the water vapor sensors and the timing of such equipage was based upon a June 2000 NWS initiative.

1. INTRODUCTION

This report represents "plans" within a plan. Part of it is written explicitly as a five-year plan for the Federal Aviation Administration (FAA) to continue to march toward a goal of an operational commercial aircraft observing system for water vapor. Part of it outlines a similar goal of the National Weather Service (NWS), whereby the commercial aircraft observing system would provide four-dimensional measurements of winds, temperature, and water vapor as a crucial synergistic complement to an evolving composite atmospheric observing system. The FAA Aviation Weather Research Program is funding the FAA activities identified in this plan and, subject to availability of funds, will continue to follow the course outlined herein. **This conceptual plan is also presented as a blueprint to achieve a national implementation of a commercial aircraft water vapor sensing system based upon a NWS initiative, which was submitted in June 2000. As a proposed initiative, there is no obligation on the part of the NWS to actually fund this at the level indicated. Thus, the numbers presented are only an illustrative example of what might be accomplished.**

One of several motives for such a plan is to help alleviate the current chaos in our National Airspace System due to excess traffic and weather delays. The Associated Press has called it the "summer of aviation discontent." FAA figures in June 2000 show 48,448 delayed flights. This was up from 41,602 delays in June 1999. Prior to this year, the summer of 1999 was by far the worst on record for delays. The Air Transport Association (ATA) says air traffic control delays in 1998 cost flyers $1.6 billion. The ATA predicts that by 2008, there will be 43% more passengers using the airways in 2,500 more aircraft, and if things are left unchanged, the additional traffic would result in a 250% rise in delays.

The FAA claims that 70% of the delays are caused by weather. Some claim weather has been overused as an excuse to cover up other shortcomings. Others say that the delay statistics are actually much worse due to carrier practices like leaving the gate within 15 minutes of the scheduled time (counted as "on time" even if the aircraft sits on the runway for hours waiting to take off) or changing listed flight duration times to much longer time periods to reduce the number of late arrivals. Weather (mesoscale convection) is the major factor, and increased air traffic is exacerbating the problem. The atmosphere is substantially under-observed for this aviation purpose. **Never has the demand for a comprehensive mesoscale network (fine structure in space/time) been more manifest than in today's world of record air traffic delays.**

There are secondary reasons for the plan. Indeed, there are other key areas of atmospheric science with significant socioeconomic impact where progress is being impeded by lack of proper information on the mesoscale atmospheric fields, especially water vapor.

While an imperfect atmospheric observing system, the commercial aircraft measurement capability provides an extremely efficient tool for filling specific space/time gaps in our current observational network. The unique role of the aircraft observing system to reduce uncertainty in our four-dimensional picture of the atmosphere's water vapor field, coupled with the available proven technology for making such measurements efficiently and accurately, cry out for the immediate implementation of such a water vapor measurement system. This plan provides a road map of how to do just that.

One could argue for a complete upgrade of our nation's upper air observing system with a variety of ground-based remote sensing systems and a number of new in-situ and remote sensing systems on commercial aircraft to complement future satellite systems. However, here we advocate an achievable incremental approach to this new composite observing system with technology that has been already proven and that would be a part of any broader composite observing system planned for the future. The second-generation Water Vapor Sensing System (WVSS-II) will be shown to possess all the requirements of a successful commercial aircraft measurement system. The existing contract between the University Corporation for Atmospheric Research (UCAR) and BF Goodrich Aerospace (BFG) for the commercial product, WVSS-II, represents another powerful incremental step toward a composite upper air measurement system.

An example of a previous successful incremental approach was taken in the improvement of the nation's radar observing network. It was realized that more powerful, more accurate, and more reliable radars could be built and deployed (replacing a very old network) and lives could be saved with more warning time for severe weather events. Though it came with a relatively high financial cost, the NEXRAD program has indeed increased warning time and saved lives.

The modest undertaking that is described here will incrementally improve our knowledge of the four-dimensional atmospheric water vapor field. This plan is relatively inexpensive, achievable, and will have high impact. Its implementation today will lead to better incremental plans for tomorrow.

Virtually every required contract is in place to implement this national program over the next five years. Considerable risk protection exists within the primary contract to ensure a safe journey. The basic funded task within the UCAR contract

with BFG completes the off-the-shelf WVSS-II and establishes certification of this product on the B-757. All subsequent aircraft type certifications and actual purchases of the WVSS-II units are contract options that will only be implemented as progress warrants. There is a further risk reduction element in the plan, whereby the overlapping demonstration of the WVSS-I and WVSS-II could lead to a NWS decision point in FY '04--whether to continue purchasing the existing off-the-shelf WVSS-II units, or to engage in a competitive request for Proposals (RFP) for a new commercial aircraft water vapor sensing system.

Section 2 presents the scientific requirements for water vapor and how they vary for various applications. Section 3 briefly discusses the evolution of commercial aircraft measurements of atmospheric quantities, and articulates specific observing system technical requirements that are necessary for the users of atmospheric data and that are essential to the air carriers involved in providing such measurements. Section 4 summarizes the second generation Water Vapor Sensing System (WVSS-II) that will initiate the national implementation and the unique advantages it has in contributing to the composite observing system. Especially important in this regard is the near perfect blend of the commercial aircraft water vapor measuring system and the next generation of interferometric satellites. Section 5 provides the road map for the implementation (who does what, when, and where) of the observing system. Section 6 provides the management and example budget information for the national program.

2. SCIENTIFIC REQUIREMENTS FOR WATER VAPOR MEASUREMENTS

There have been hundreds of articles in the scientific literature on the role of water vapor (also water in liquid and solid form) in mesoscale convective initiation, evolution, and decay; on the role of water vapor in predictability; on diagnostic case studies involving water in its various forms; on moist physics; and on model simulations involving water vapor. Perhaps one of the most direct results pertinent to our purposes here is the study by Crook (1996), which showed that an uncertainty in the value of relative humidity in the boundary layer of plus or minus 5% leads to an overestimate or underestimate of precipitation amount by a factor of 2-3 respectively. This premium placed upon the accuracy of water vapor is extremely disturbing when we see where we stand today in the analysis and prediction of this variable. Figure 1 is a representation of a series of predictions with the Rapid Update Cycle (RUC) model developed by the Forecast Systems Lab (FSL) of NOAA (Benjamin, 1999). The various panels in Figure 1 show error statistics of forecasts 1, 3, 6, and 12 hours into the future respectively--all valid at the same time period. As the analysis/prediction cycles shorten, we see a systematic improvement in error statistics of temperature, height, and wind--as one would expect. However, there is no systematic improvement in the relative humidity field--all forecasts are equally bad--and the magnitude of the error is atrocious, approaching 20%. When we compare these deplorable results for relative humidity with the accuracy requirement shown by Crook (1996), it is no wonder that we have far to go in precisely predicting convective regions for aviation interests and that our operational predictions of precipitation amounts need significant improvement.

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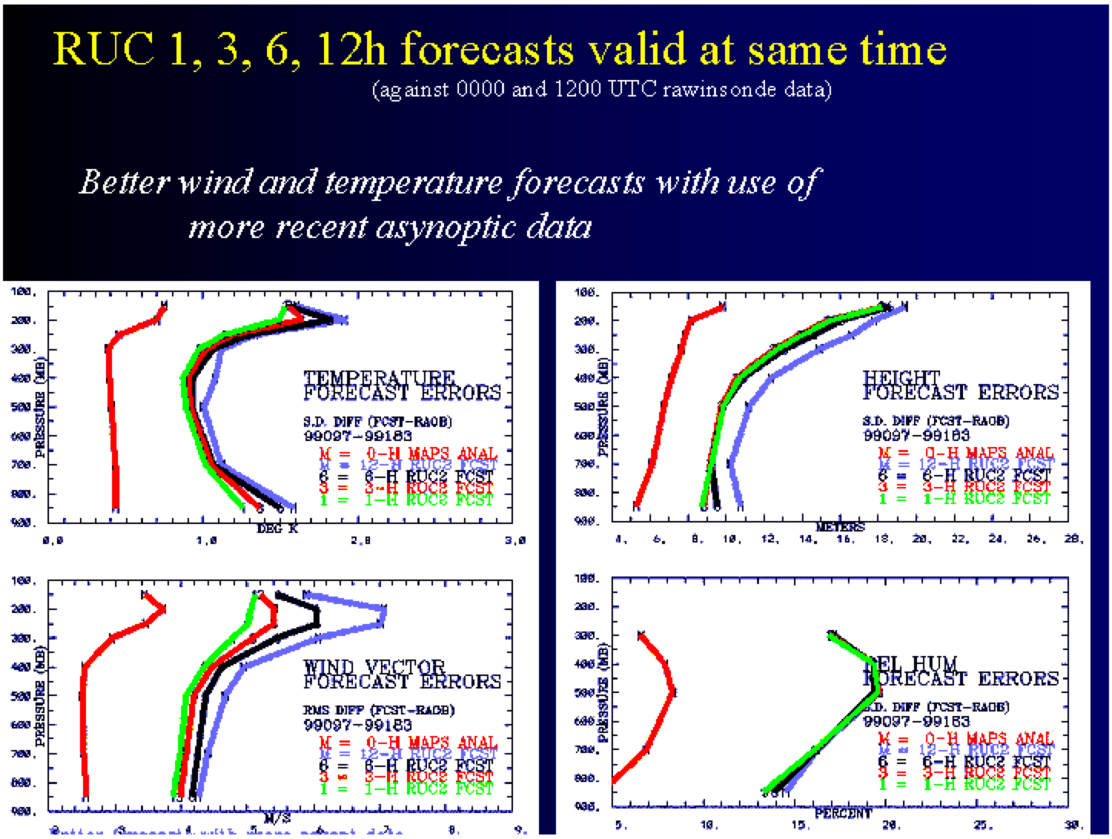

Figure 1. MAPS verification of analysis and of predictions of 1, 3, 6, and 12 hours into the future (valid at the same time period). Provided by Sam Benjamin.

Mesoscale modelers would suggest that the three main reasons for such a disastrous state of affairs would be (i) poor initial conditions on the mesoscale, especially for water vapor, (ii), improper modeling of sub-grid scale effects (though this becomes a smaller influence as the mesoscale prediction grids in space/time become finer and finer), and (iii) uncertainties in resolvable scale moist physics parameterization. Relevant comments on these points will follow later.

One also has a further indication of the role of water vapor in today's primarily synoptic scale operational weather prediction models from the recent North American Observing System (NAOS) report on radiosondes and aircraft data (wind and temperature information only)--see NAOS Report, July 2000. Numerical sensitivity testing with the NWS's National Center for Environmental Prediction (NCEP) operational Global and Eta analysis forecast systems and the RUC indicated that the radiosondes' data were effectively redundant with the vertical analysis/descent profiles of winds and temperatures at 14 co-located sites. The aircraft data, decoded at Aeronautical Radio, Inc. (ARINC) and sent to the NWS, called the Meteorological Data Collection and Reporting System (MDCARS), was substituted for radiosonde data and no significant impact on the forecasts were found. The lack of temperature and wind data above jet-flight levels, and the complete absence of moisture information in the MDCARS data resulted in no meaningful effect in forecast performance.

An exception to the above results was noted in the NAOS Report, with regard to moisture data, especially in the Eta and RUC systems, which had significant effects on analysis in the immediate vicinity of the radiosonde sites from where the data had been eliminated. The NAOS Report further notes that the moisture field rapidly adjusted to nearly the same values in three separate runs: (i) RAOBS and MDCRS included, (ii) MDCARS substituted for RAOBS, and (iii) both RAOBS and MDCARS withheld. Based upon these runs, the NAOS Report noted that the loss of moisture data from a few sites had no impact on an already **under specified field**, with the result that there was little or no impact on forecasts of the 0-12 hour precipitation amounts. A notable footnote from the NAOS Report was "Observing systems with greater spatial density and vertical resolution of moisture fields are required, along with advances in data assimilation systems, to extract the maximum possible information."

The problem with the initial conditions for water vapor analyzed to a three-dimensional mesoscale grid are far more serious than one would expect from another variable (e.g., pressure) in a synoptic scale analysis. It is not just that the exact location of a feature like a low pressure center is misinterpreted or that its movement is not precisely known (because of uncertainties in the wind field), rather it is that entire thermodynamic features (**small-scale three-dimensional constructs**) are entirely missing from the initial analysis--or these small-scale features are mutilated or miscast in the analysis due to the poor observational network. In fact, our nation's upper air measurement system is woefully inadequate for water vapor (and hence aviation interests) with a radiosonde program with a 12-hour time resolution and a 400 km spatial resolution [satellites, while exhibiting good horizontal and temporal resolution do not help this variable because of their very coarse vertical resolution coverage].

How do we know that we are missing these water vapor features? Intuitively, inspecting the small-scale variability in cloud features from the ground or from space or noting the spatial variability of precipitation from radar images might give one cause to suspect that highly variable space/time water vapor features do exist. However, these processes are highly nonlinear, involve moist physics and scale interactions and **may not be due** to antecedent small-scale variability in water vapor.

<="" a=""> It is now known that water vapor fine structure exists and we know this from a number of field studies with high space/time observational coverage. We also know this every time we turn on a vertically pointing, continuously sensing, ground-based remote sensing system such as an interferometer, differential absorption lidar (DIAL), or Raman scatter lidar. Figure 2 from Melfi, et al (1989) shows such a time record for mixing ratio over a period of 10 hours. One observes a clear mesoscale structure in these water vapor time cross-sections. These are of course, invisible to the naked eye. In the boundary layer (whether that boundary layer is predominantly wet or dry) and in the 3-5 km-thick layer immediately above the boundary layer (whether that layer above the boundary layer is relatively wet or dry) one detects these alternating thin layers of wet and dry air from these ground-based remote sensing devices. These thin "lenses" of water vapor-rich air can have a vertical scale as small as 200-300 meters and may have a horizontal extent as large as a few hundred kilometers.

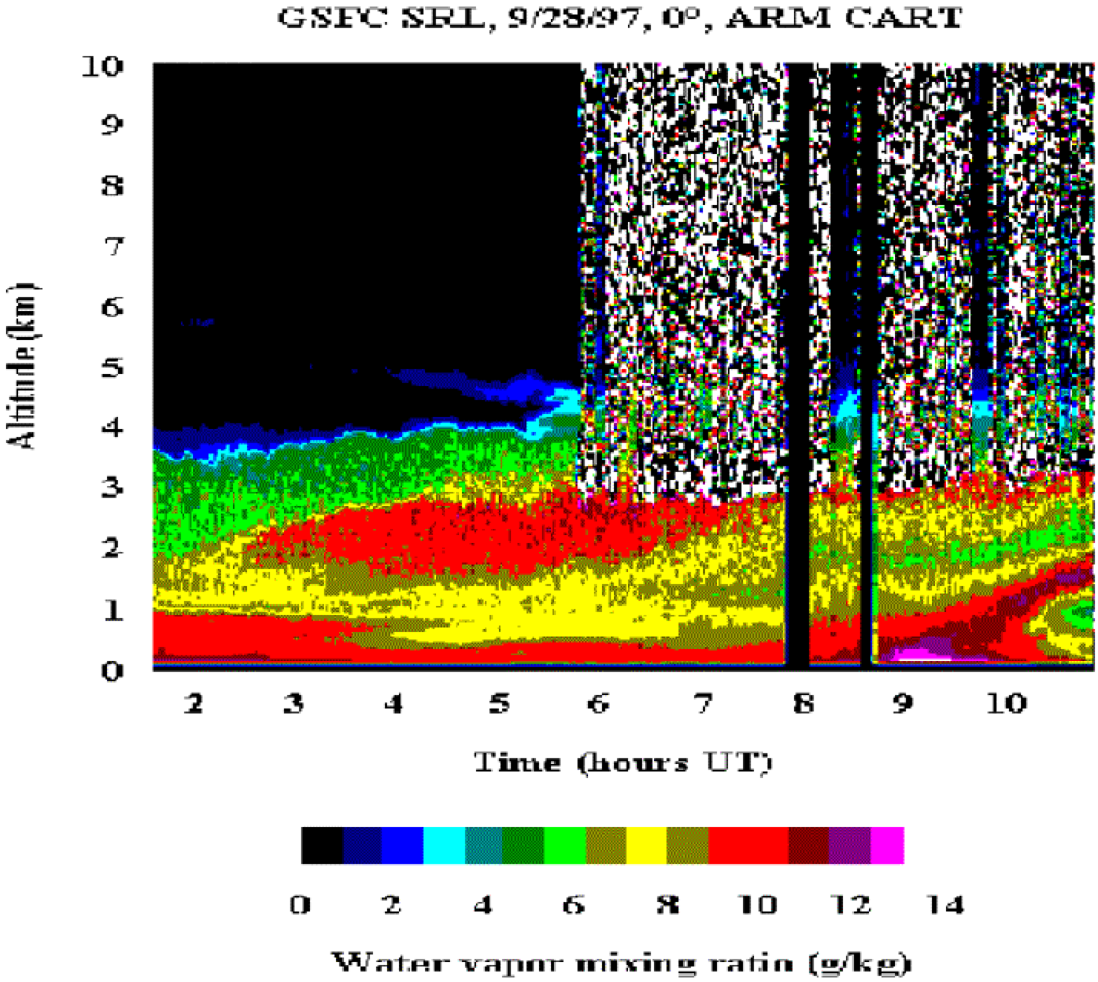

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Figure 2. Cross-section of mixing ratio versus time from measurements of a Raman scatter lidar.

There are a number of reasons that such a mesoscale layering of water vapor might occur. Some of these include: advection of water from different sources in a vertical wind shear environment, motion around frontal zones, evapotranspiration from the terrain below, post-dissipation of an individual thunderstorm cell, or dissipation of a previous mesoscale convective system (MCS), etc.

One also knows that water vapor is like a "volatile jet fuel" to the atmosphere--in this case fueling convection. Condensation of water vapor to liquid can quickly release 50 Joules/gram of energy in the lower troposphere [from L_q = (2,500 J/g)(20 g/kg); for comparison, a very strong wind of 45 meters/second in this region would have kinetic energy of 1 Joule/gram.] Just how these small-scale water vapor features might contribute to the development or decay of convection, particularly a MCS is just one of many questions about convection and MCSs that are unanswered. MCSs are multi-cell, long-lived convective systems. Such a system is composed of water vapor in all three forms: water vapor, liquid water in the form of a spectrum of cloud water droplet sizes and a spectrum of raindrop sizes, and solid water in the form of a spectrum of cloud ice crystal sizes, grauple, hail, and snow.

The MCSs are the weather elements that can particularly impact air traffic, rather than individual cells, especially when they occur near major traffic hubs. A range of these MCSs would have horizontal scales of a few tens of kilometers to 300 kilometers, and lifetimes of three hours or more. Combining these dimensions with the vertical structure seen in water vapor cross-sections, one can derive a suggested set of space/time requirements for an initial look into the mesoscale four-dimensional water vapor field:

horizontal resolution:	16-150 km
vertical resolution:	100 meters
time resolution:	1.5 hours (90 minutes)

<="" a=""> These values match a 2-delta(x) observing system requirement for the minimum size features identified above. One may find later that these preliminary requirements are not yet fine enough, but they represent a good achievable starting point. We know for example, that there are often invisible "water vapor sheets" (similar to the visible "cloud sheets") located at the top of the convective boundary layer (Hanssen et al, 1999). These horizontal convective rolls can be several 100 kilometers long and have horizontal band separation of only 2-4 km. The roll updrafts are warmer and moister than the roll downdrafts, but the roll updrafts contain the moisture values that provide the best estimate of the potential for deep, moist convection (Weckwerth et al., 1996).**Obviously, no single**

observing system can match these requirements today However, **satellite** systems (especially future satellite systems) and the **commercial aircraft fleet** called for in this plan can meet these specifications--at least in the context of four-dimensional variational analysis. More on this subject is covered in Section 4.2.

A final reason for poor model performance was expressed as imperfect knowledge of the explicit moist physics occurring **at the grid-scale, which is resolved**. Figure 3 shows a sketch of the mixing ratio variables (q_v,q_c,q_i,q_r,q_s for water vapor, cloud water, cloud ice, rain, and snow respectively) and their interaction as depicted in a NCAR mesoscale model (Dudhia, 1989; there is a later version of the model that would also have a mixing ratio for graupel added). There are approximately 20 tuning coefficients involved in the moist physics interactions between these mixing ratio variables. Most of these coefficients are known quite well, but some are not. The water vapor mixing ratio is clearly the dominant one in Figure 3. We must both improve the knowledge and physical interactions of this variable with the other mixing ratios in order to improve model predictions of convection, severe weather, ceiling and visibility, and precipitation. The composite system of many commercial aircraft and radars will help capture this knowledge.

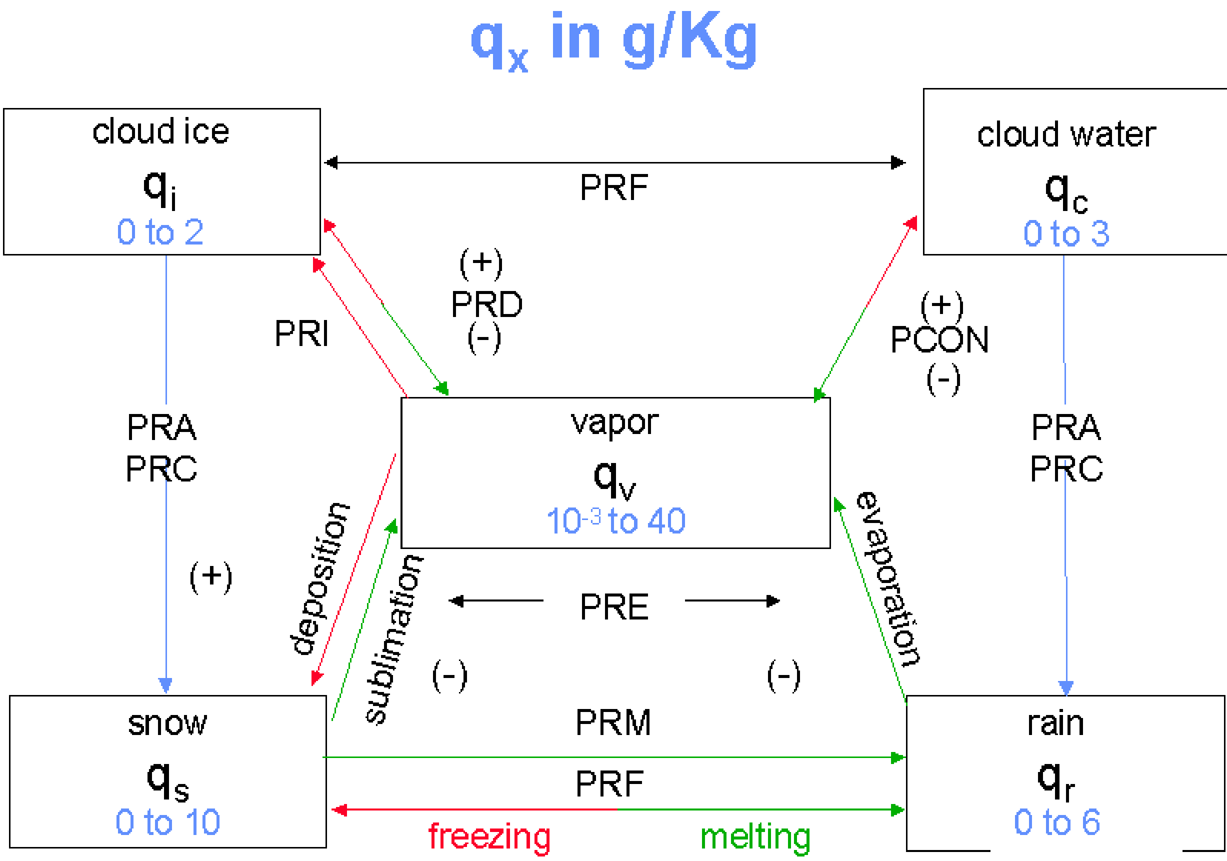

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Figure 3. Illustration of the mixing ratios (range of values shown in g/kg) which are prognostic variables in the National Center for Atmospheric Research mesoscale model. Original illustration courtesy of Dudhia (1989).

There is a growing body of evidence suggesting that observations on the scale outlined above will have an impact on understanding and subsequently predicting the MCSs. Bryan and Fritsch (2000) list approximately 40 scientific papers that speak of "slab convection". The entire low-level mesoscale environment is ascending as opposed to ascent only in individual cumulonimbus updrafts, which can emerge from the slab at mid and upper levels. Under certain conditions, the atmosphere convectively overturns in a manner resembling mesoscale slabs (or sheets) of ascending air overrunning slabs of descending air. An explanation of the initiation and maintenance of this convection is partially provided by the "moist absolutely unstable layers" seen in the radiosonde data from Bryan and Fritsch. Such layers are also seen in the water vapor information from commercial aircraft and are found to be consistent in space and time. These unstable layers occur with a vertical depth of greater than 100 mbs in about 2-3% of summertime profiles. These slabs are typically several hundred kilometers wide in the cross-flow direction and a few tens to several hundred kilometers wide in the along-flow direction (e.g. Roux et al, 1984; Chong et al, 1987; Smull and Augustine, 1993; Trier and Parsons, 1993).

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3. EVOLUTION OF COMMERCIAL AIRCRAFT OBSERVATIONS AND SYSTEM REQUIREMENTS

3.1 History

The history of the use of commercial aircraft as a source for atmospheric measurements is described by Fleming (1996). Obtaining measurements in real time is key to aviation and NWS needs. The airline community, represented by Aeronautical Radio Incorporated (ARINC), a company partially owned by the air carriers themselves, developed a real time, line of sight VHF digital communication system in the late 1970s. The first real-time distribution of wind and temperature information from a commercial airline (American

Airlines) occurred on this system in 1979 as part of the Global Weather Experiment (Fleming, et al, 1979). The communication system was called Aircraft Communication and Reporting System (ACARS) and has progressed to where it is used today for applications in the general categories of Airline Operational Control (gate departures and arrival time, runway departure and landing time, fuel on board, crew hours, etc.), Air Traffic Services, Air Traffic Management, and Weather Support.

In 1989, a contract was signed between the FAA and the ARINC to provide a subset of the ACARS data to the National Weather Service (NWS). This data set is the MDCARS data referred to in the previous section and it consists of winds and temperature only. The NWS now shares the funding of these data, which is decoded by ARINC (working on a 24-hour per day, seven day a week schedule) and sent to NCEP of the NWS in the BUFR format.

The FAA began funding the lead author of this plan in a research effort on the feasibility on measuring water vapor from a commercial aircraft in 1991. The results were published in a FAA Technical Report (Hills and Fleming, 1994) and of the many different measurement concepts available for water vapor, only three were considered acceptable for the operational environment of a commercial aircraft--diode laser technology for the measurement of water vapor mixing ratio, thin-film capacitors for the measurement of relative humidity (RH), and sophisticated chilled mirrors for the measurement of dewpoint. [Note that all three measures of water vapor information (mixing ratio, relative humidity, and dewpoint) are interchangeable if you know the temperature and pressure on the aircraft, which is available; thus, any of these water vapor measures can be downlinked to the ground.]

A contract was awarded to the Lockheed Martin Corporation (LMC) in July of 1995 for the first-generation Water Vapor Sensing System (WVSS-I). This was a thin-film capacitor technology that had some known limitations, but the desired diode laser approach was not bid in this competitive procurement. At the time, this technology was too expensive. This has since changed (see Section 4).

Six United Parcel Service (UPS) B-757 aircraft have been flying the WVSS-I. Figure 4 shows a picture of the UPS aircraft with the WVSS-I shown in the insert. Approximately a quarter of a million quality-controlled reports from these aircraft (covering the time period from July 1999 to present) are available at the University Corporation for Atmospheric Research (UCAR) and are available on the Internet. These aircraft have AlliedSignal avionics, and the WVSS-I software downlinks the water vapor mixing ratio. A build-up of UPS and American Airlines B-757 aircraft equipped with the WVSS-I is in progress and will stop at 50 aircraft. These aircraft have Teledyne avionics and the WVSS-I software for this avionics downlink RH. The new ARINC 620 Specification for Meteorological Formats has RH as the water vapor variable, and this format will serve the new second-generation WVSS (WVSS-II) described in Section 4. These data are now part of the MDCARS data collection for the NWS. Examples of these data are shown in Figures 5, 6, and 7, provided by Wayne Feltz.

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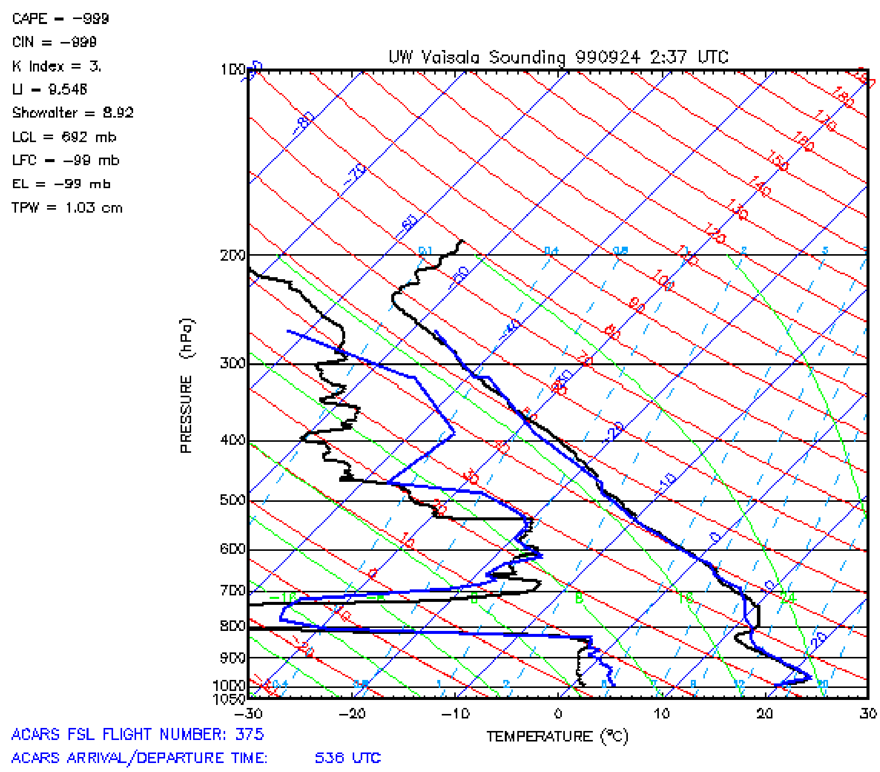
Figure 4a.--(insert) A close-up of the Water Vapor Sensing System (WVSS) probe (3 inches extend into the atmosphere and 5 inches extend beneath the surface of the fuselage.

Figure 4b. The probe is located on the left side of the aircraft in the area of the black stripe tailward of the cockpit door. Photos courtesy of Lockheed-Martin, BF Goodrich Rosemont Aerospace, and United Parcel Service.



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<="" a=""> **Figure 5.** Black profiles are radiosonde profiles (temperature on the right and dewpoint on the left) and blue profiles are corresponding data from the commercial aircraft. Information provided by Wayne Feltz, University of Wisconsin, Louisville, Kentucky, September 24, 1999.

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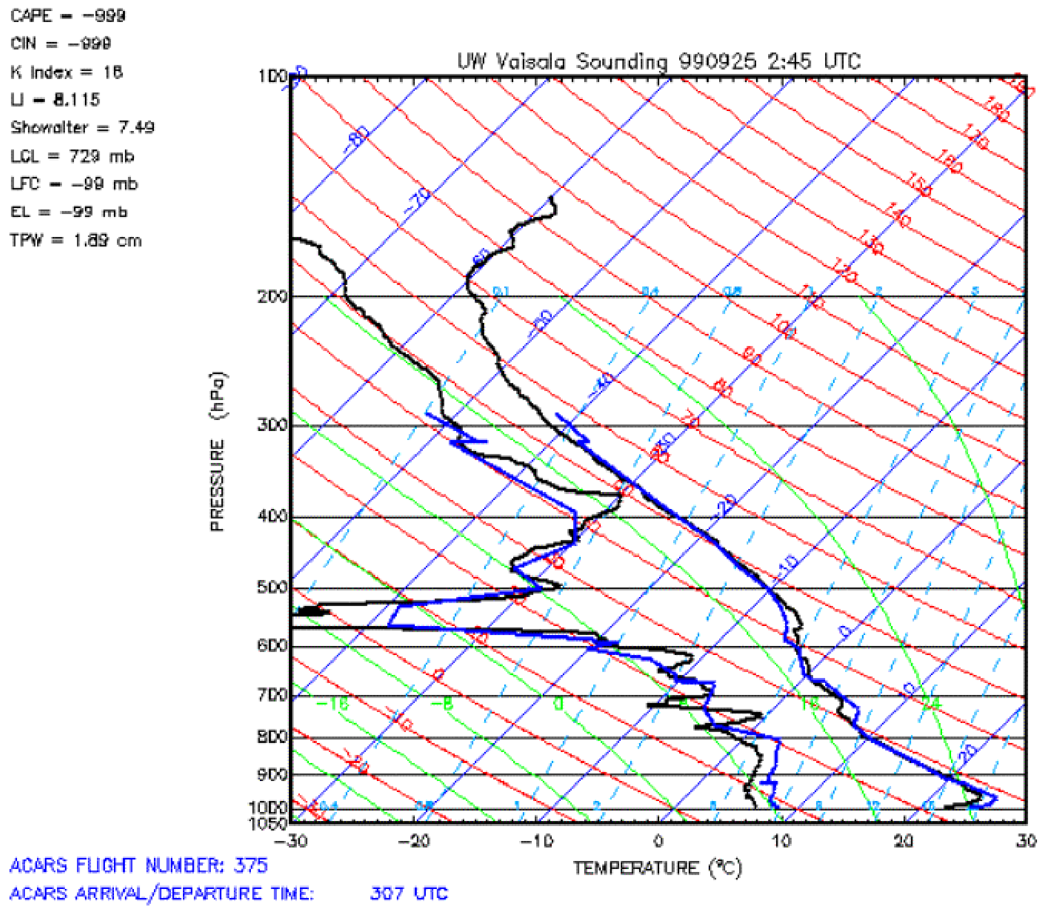

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<="" a=""> **Figure 6.** Black profiles are radiosonde profiles (temperature on the right and dewpoint on the left) and blue profiles are corresponding data from the commercial aircraft. Information provided by Wayne Feltz, University of Wisconsin, Louisville, Kentucky, September 25, 1999

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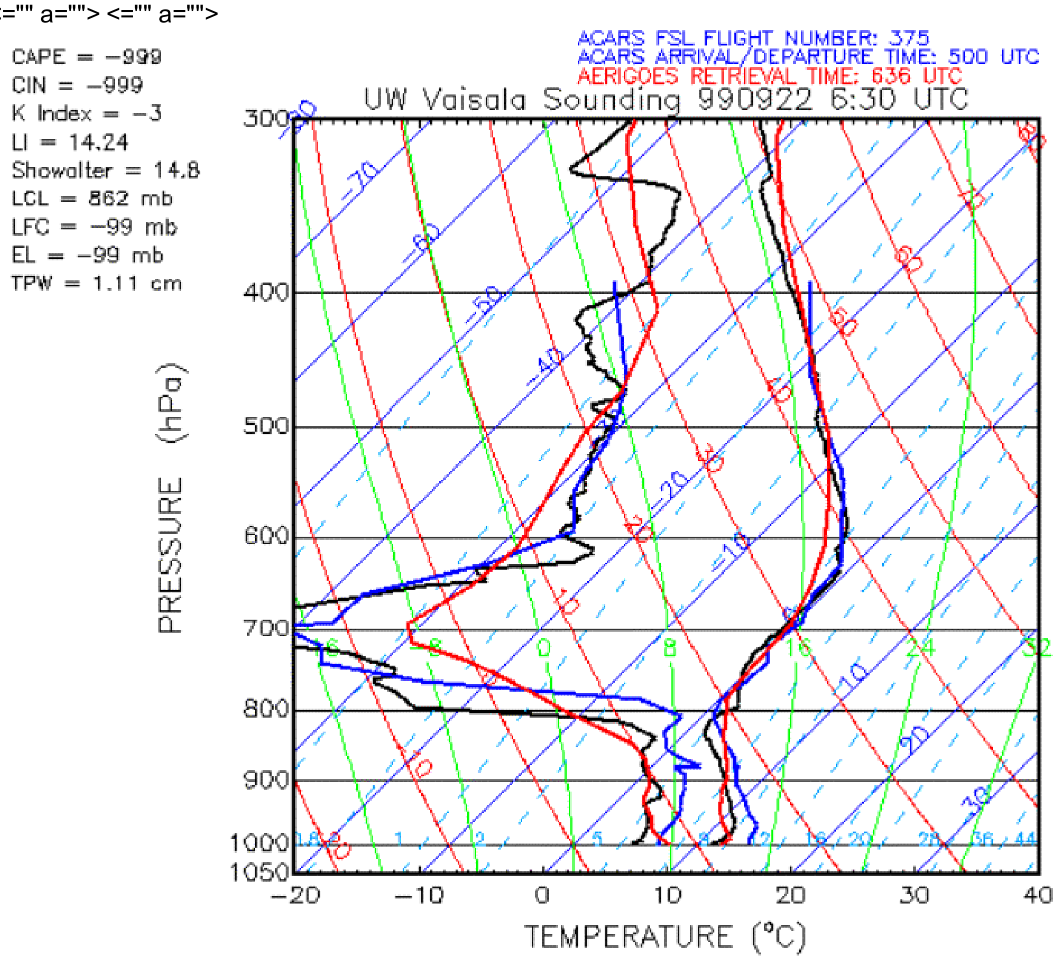

Figure 7. Same information as in Figures 5 and 6, but the red is the data from the University of Wisconsin interferometer (called AERI). Data from Wayne Feltz of the University of Wisconsin, Louisville, Kentucky, September 22, 1999.

<="" a=""> 3.2 System Specifications

The specifications for the WVSS-I have been made more demanding for the WVSS-II. These specifications are for the benefit of the user of the water vapor information (high accuracy, rapid response time, high sensitivity, etc.) and for the benefit of the commercial air carrier providing the data. Of course, no equipment like the WVSS-II can fly on a commercial aircraft unless a Supplemental Type Certificate (STC) has been obtained through and approved by the FAA. The attainment of STCs for various types of commercial aircraft has been a major part of the past WVSS activity and is a major part of this plan. A brief summary at each of these system specifications, shown in Table 1, is provided below.

Table 1. Specifications for the WVSS-II

I. Performance Requirements

P1 Accuracy:	<= 5% of signal at all altitudes
P2 Response time:	<=3 seconds to 10,000 feet <=6 seconds about 20,000 feet
P3 Detection limit:	<= 2 ppmv
P4 Sensitivity to wetting:	<= 1 min. recovery to 5% accuracy
P5 Maintenance Interval:	>= 2 yrs. for necessary maintenance or recalibration
P6 Repair time:	<= 60 min. to perform maintenance in P4

P7 Weight: Incremental weight (over that of conventional TAT probe) <= 10 lbs.

P8 Environmental range of P1-P7: 100-1100 hPa and -85 to +55C.

II. Output Requirements

O1: Real-time output of mixing ratio according to ARINC 620

O2: Recorded output (during check-out phase) of the WVSS-IIs (mixing ratio, pressure, and temperature), standard TAT (static temperature), and Mach number.

Accuracy

Therandom error or measure of accuracy of satellite water vapor profiles ranges from about 20-40% of the satellite signal for today's systems, and will be in the range of 10-20% for the next generation satellite systems. The accuracy is poorest near the Earth's surface. The range of radiosonde accuracies varies from country to country but generally falls in the range of 5-20% with several important caveats. The accuracy of radiosondes is better near the Earth's surface. It can be as low as 4% in the boundary layer if: (i) there is no systematic dry bias (as exists in some systems), (ii) the sensor was properly calibrated and hence has no systematic error, (iii) the sensor remains in calibration over time, (iv) sensor wetting has not occurred as the balloon ascends into clouds and/or precipitation.

Our goal is for the commercial aircraft sensor to be more accurate than radiosondes. It is believed that this may have been achieved in the WVSS-I and that accuracy will be further improved with the WVSS-II. The WVSS-I can also achieve <= 4% error in the boundary layer if: (i) the initial calibration is good, (ii) the calibration remains good over time, and (iii) sensor wetting is minimized (this occurs automatically in the aircraft by the probe design).

In the upper atmosphere, particularly in the cold upper troposphere, the radiosondes have a profound problem of being biased dry. Errors can be 15-38% in ice clouds (Miloshevich, et al., 1998). This is due to the very slow response time of thin-film capacitors in the very cold environment. Fleming and Braune (2000) have described the performance of the WVSS-I in this cold environment. Measurement of RH on a fast-moving aircraft has two distinct features, one good and one bad, that are due to the same cause�the dynamic heating inside the measurement probe due to the aircraft's Mach number (speed). Figure 8 (reproduced from Fleming and Braune (2000) where a detailed discussion can be found) shows that this "Mach number effect" becomes significant for Mach numbers greater than Mach = 0.65 at the very cold temperatures at flight level. Most aircraft speeds at flight level range from Mach = 0.75-0.82. The good news is that the dynamic heating warms the measurement environment by as much as 30C and the sensor response time dramatically increases to provide good data where the radiosonde data would be unreliable. The bad news is that same dynamic heating or "Mach number effect" leads to a random error in the measurement of 10-17% depending upon temperature and Mach number. While this random error can be averaged out in climate studies, it is a problem in weather research. **Note that this negative effect is not present for systems that measure mixing ratio (like the WVSS-II, described in Section 4) or for systems that measure the dewpoint directly (see Hills and Fleming, 1994 and Fleming, 1996).** It should also be stressed that the Mach number effect is not strong enough to significantly impact the commercial aircraft ascent/descent data because the aircraft is moving at less than Mach = 0.4 below 20,000 ft.

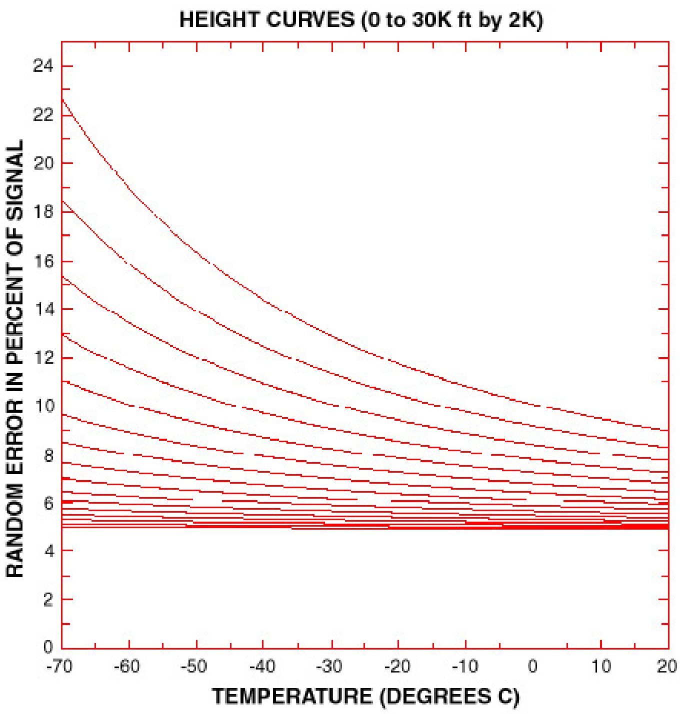

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Figure 8. Random error in percent of signal for the WVSS as a function of temperature and as a function of height. The height curves start at the bottom as zero height, and then each subsequent curve is 2,000 feet higher until the top curve of 30,000 ft. Mach number

(M) has been effectively converted to height (Z) by M = 0.2 + 0.61(Z/30,000).

The more stringent specifications for the WVSS-II system accuracy are <= 5% at all levels of the atmosphere. The accuracy in the boundary layer will be about 3% and the accuracy in the stratosphere (when aircraft occasionally fly there) will be <= 5%.

Response Time

<="" a=""> Response time has already been mentioned above. Because of the speed of the aircraft, this is an important issue for obtaining representative data. No viable commercial aircraft water vapor technology can match the speed of the WVSS-II's diode laser in achieving a fast response time (certainly not thin-film capacitors nor sophisticated chilled mirrors--or even the surface acoustic wave (SAW) type devices). The response time of the diode laser is only limited by the speed of the air moving through the measurement chamber. This device can easily meet the response time specifications indicated in Table 1.

Sensitivity

Sensitivity to very low values of moisture content is not very important to the weather prediction problem, but is important to the climate community concerned with global warming. Water vapor is the most powerful greenhouse gas, and its abundance in the upper troposphere and in the normally extremely dry lower stratosphere is an important variable to monitor. This is the reason the specification for sensitivity is set so low in Table 1. The WVSS-II can meet this specification of 2 ppmv (parts per million by volume). For typical low values of water vapor in the lower stratosphere, a range of water vapor mixing ratios of 3-5 ppmv are found. Figure 9 shows how well this diode laser system works in an "open path" system flown on the NASA ER-2. Also shown is the Harvard Lyman-Alpha research instrument, described by Hinsta, et al (1999), which used the diode laser system as the norm for comparison.

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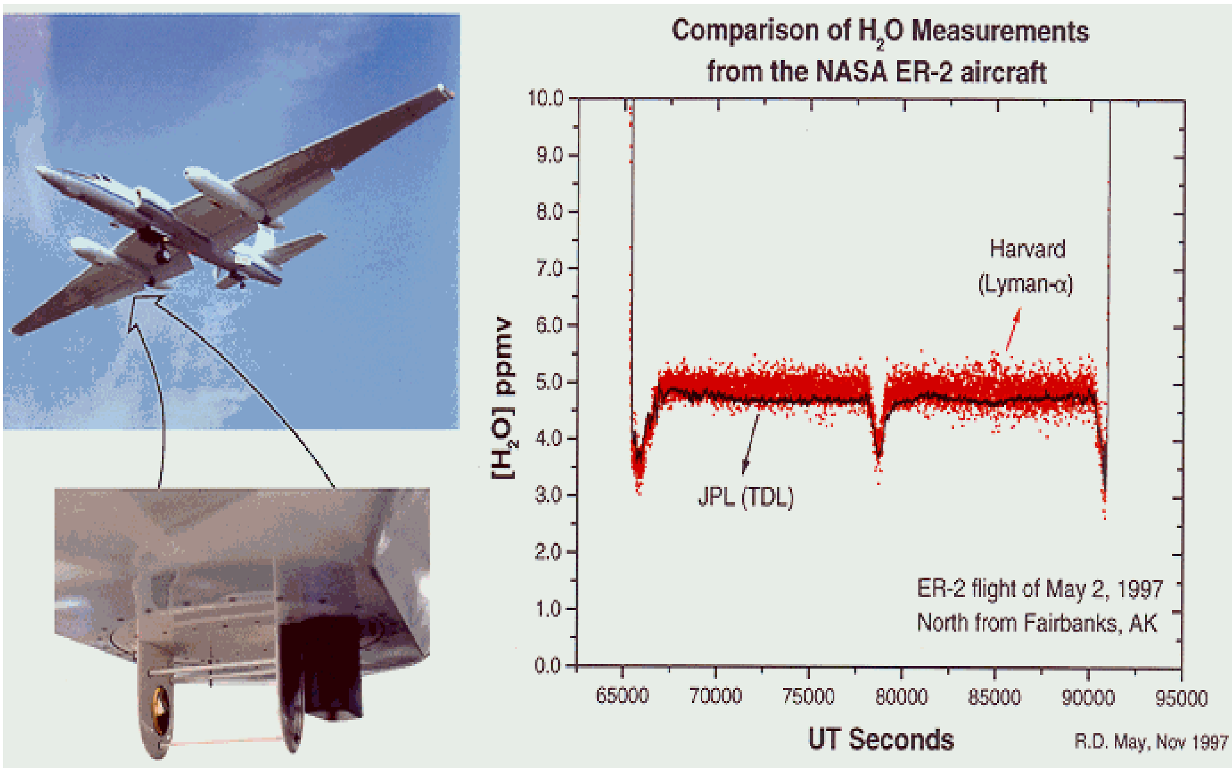


Figure 9. Comparison of open path diode laser with Harvard Lyman-Alpha during ER-2 flight into the lower stratosphere.

Sensitivity to Wetting

<="" a=""> Sensor wetting on radiosondes was alluded to above. This wetting affects both temperature and RH measurement on radiosondes. BF Goodrich Aerospace (formerly Rosemont Aerospace), who manufacture 95% of the world's total air temperature (TAT) probes on commercial aircraft and also manufacture the WVSS-I and WVSS-II, have carefully designed their probes to eliminate liquid or solid water elements from entering the temperature measurement chamber of their probes. However, we know from experience at the National Center for Atmospheric Research (NCAR) that no probe is perfect in this regard. BF Goodrich Aerospace (BFG) did use a new probe design (also used on later version B-747s, B-767, and B-777 aircraft) for the WVSS-I. This probe was 50% more efficient in eliminating ice crystals from entering the temperature measurement area due to the aerodynamic design changes that were made. This subject of sensor wetting is still somewhat uncertain. The specification in Table 1 is achievable by the WVSS-II. Just how much better it can be than the specifications is uncertain. We do know that the aerodynamics of the probe and the speed of the aircraft allow a faster "drying period"--both for the temperature and water vapor sensors--than occurs for the radiosondes.

Periodic Maintenance Interval

This subject begins a discussion of those specifications that are in the interest of the air carrier who is supplying the water vapor information from the aircraft. The air carrier is in the business of moving people and packages. This is a complex business with a low profit margin. Adding another piece of equipment to make water vapor measurements is very low on a carrier's priority list. However, over time we have seen a growing acceptance that the water vapor sensor will benefit all concerned and carriers have been willing to add it to the aircraft--if maintenance is very infrequent and the weight of the sensor is very light.

The recommended periodic maintenance interval for the WVSS-I was six months (to recalibrate the sensor). However, due to the UPS switch of avionics vendors from AlliedSignal to Teledyne--and the subsequent year delay in Teledyne hardware and software--some of the WVSS-I units have flown up to 14 months without recalibration. On some aircraft, we see no impact of this long operating period, however on at least one aircraft we have seen a degradation of performance. A subsequent switch of this WVSS-I unit with a new unit did show an improved performance.

The specification for the Periodic Maintenance Interval is set at two years. The goal of the WVSS-II system is 2+ years for periodic maintenance, but two years are assumed in the financial numbers of this plan.

Repair (Replacement) Time

Repair time here is simply the time required to remove the WVSS-II probe and replace it with a spare probe. This is only expected to be required every two years. The purpose is to recalibrate the moisture-sensing element. Since water vapor is not yet a "flight critical" item, this replacement can be performed any time at the carrier's convenience. There are a number of predetermined maintenance periods for commercial aircraft: A-checks, B-checks, and C-checks--each being a more sophisticated evaluation respectively. The time interval between these scheduled checks varies with the aircraft type, but it is frequent enough that the WVSS-II probe replacement could be performed at any of these checks if the replacement time is less than 60 minutes--hence the specification in Table 1. Since the WVSS-II also is the aircraft's TAT probe (and temperature **is** a "flight critical" item), this replacement time will be as quick as possible--approaching that for today's TAT probe.

Weight

An old airline standard formula for calculating the cost of additional fuel for adding new equipment to the aircraft was "one dollar per pound per week." This value has probably gone up over this past two years, but carriers are not concerned with weights less than 10 pounds. Our participating air carriers have flown the WVSS-I without any "carrying" charge. The government agencies (FAA and NOAA) have paid for the WVSS-I acquisition, installation, and maintenance. **The specification for weight is thus less than 10 pounds (over that of the conventional TAT probe) for the WVSS-II. At this low weight the airlines would not have a carrying charge**. The WVSS-II will easily meet this specification and weigh less than 5 lbs. This is because the new WVSS-II is the same TAT probe that exists on each aircraft type--except that the probe now measures both temperature and water vapor information **simultaneously** and **independently**. The WVSS-II uses the same aperture in the aircraft skin as the existing TAT probe for that aircraft type. The WVSS-I had a unique probe on the opposite side of the aircraft, thus there was a second aperture in the aircraft skin. We knew that this was not the ultimate way to go operationally, but it was an acceptable way to prove the water vapor measurement concept on commercial aircraft.

4. WVSS-II ROLE IN A COMPOSITE OBSERVING SYSTEM

4.1 The WVSS-II

The second generation Water Vapor Sensing System (WVSS-II) began with FY 2000 funds, proceeding in parallel with WVSS-I evaluation efforts. The WVSS-II is significantly superior to the WVSS-I in three important ways.

(1) Accuracy: The measurement concept is that of Randy May (formerly NASA JPL, now SpectraSensors) where a single mode diode laser is capable of fine accuracy and precision (even into the stratosphere) and represents the "standard" of water vapor measurement accuracy today. These diode lasers were hoped for in the WVSS-I procurement, but they were not bid at that time because of cost.

(2) Probe replacement on aircraft: This WVSS-II probe independently measures temperature and water vapor, and is a replacement for the existing TAT probe on commercial aircraft. It fits into the same hole, unlike the WVSS-I that fits into a larger aperture on the other side of the aircraft.

(3) Maintenance Interval: The method of implementation of the diode laser of the WVSS-II allows a maintenance interval of two+ years as opposed to the six month interval proposed for the WVSS-I.

Further discussion on each of these points follows below.

The use of diode lasers to measure accurately the atmospheric water vapor mixing ratio has been proven on high altitude balloons and NASA research aircraft (cf. May, 1998). The measurement concept uses Beer's Law in the form

$I = I_o exp[-sigma(nl)]$

where

I = laser intensity at detector

I_o = laser intial intensity

sigma(nl) = absorbance

with

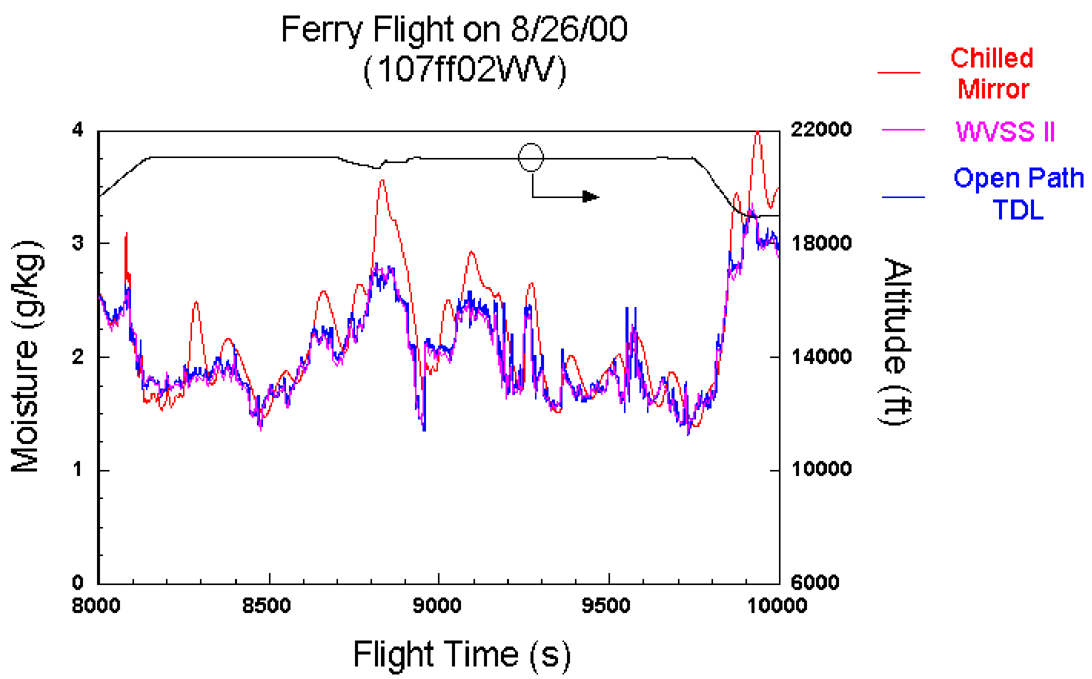
n = number density of absorbing species

l = optical path length

sigma = molecular absorption cross section

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

The measurement concept, technology, and software of the above scheme have all been proven. A UCAR contract with SpectraSensors to reduce the path length to a short distance inside a standard TAT probe was primarily a size-reduction engineering problem. A key to this contract initiation was the fact that SpectraSensors could now provide highly reliable, long-lifetime, single-mode diode lasers at reasonable cost. With prototypes produced from this contract, laboratory tests and flight tests allowed improvements to be made. Figure 10 is a result from a flight test of the WVSS-II on the NCAR C-130 in August of 2000. This version is still not the final product, but one can see that the diode laser system is working inside the BFG TAT probe. This was mounted on the C-130 next to the diode laser "open path" system, which is now standard equipment for this aircraft (cf. Gandrud, 2001). With the joining of BFG (manufacturers of 95% of the world's commercial TAT probes) and SpectraSensors, a UCAR contract was initiated to provide a new off-the-shelf TAT probe that would simultaneously and independently provide both temperature and water vapor information. This off-the-shelf product is the WVSS-II. A picture of the WVSS-II mounted next to the open path system is shown in Figure 11.



<="" a="">

Figure 10. Initial WVSS-II flight test result on the NCAR C-130. WVSS-II data is raw data gathered at 4 Hz. Standard C-130 chilled mirror instrument data is raw data with "overshoot" and false "bottoming out" not yet removed by NCAR processing.

<="" a=""> <="" a=""> 

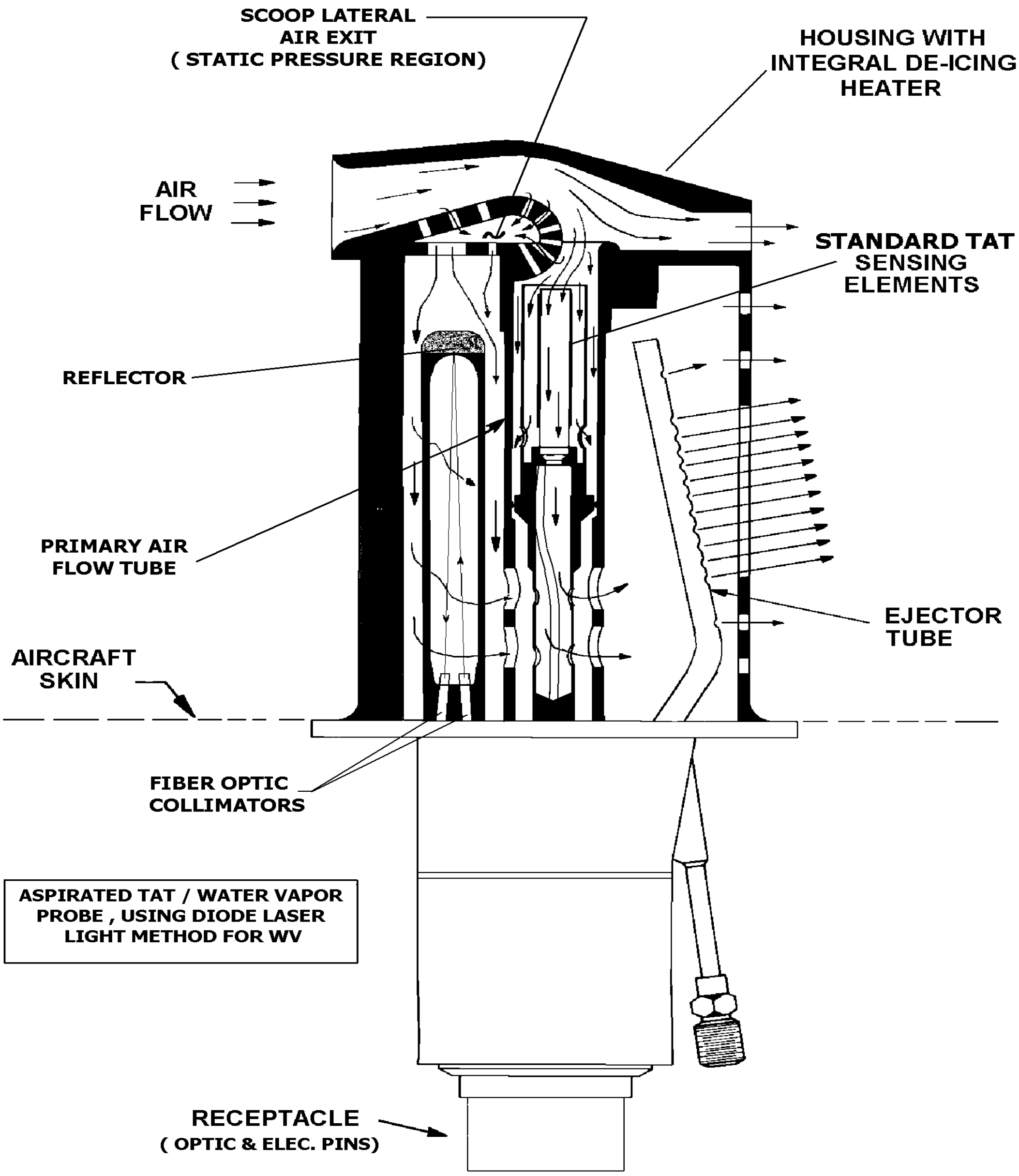
<="" a=""> **Figure 11.** Picture of WVSS-II mounted next to open path diode laser system on NCAR C-130.

<="" a="">

The accuracy of the WVSS-II will be <= 5% for **all levels of the atmosphere**. The sensitivity or detection limit will be 2 ppmv. This is important for the occasional stratospheric measurement where values as low as 4-5 ppmv are encountered. For typical values of pressure and temperature found in the lower stratosphere, differences between 4 ppmv and 5 ppmv produce RH values of 2.3% and 2.9% respectively. Since the ARINC 620 format allows RH values to be downlinked to the nearest tenth of a percent (for RH values below 10%), (see Fleming (2000)), this detection limit and precision closely matches the downlink capability.

Combining the temperature and water vapor measurements into a single probe is a requirement for an operational water vapor sensor on a commercial aircraft--if the sensor is to be retrofitted to existing aircraft. If would be possible to work with airframe manufacturers like Boeing and Airbus to design a separate probe, but this would mean finding a location on the aircraft, making a new aperture in the skin, adding more weight to the aircraft, and requiring a more extensive certification process. This approach would raise the cost of such a new sensor. Modifying the existing TAT probe and making the WVSS-II fit into the existing aperture for the TAT probe saves a considerable amount of money--both initially and in the future installation. The only concern is that the temperature measurement (which actually comes from two temperature sensors) is made independent of the water vapor measurement and is not affected by it. This is part of the task of BFG. Proving that the temperature measurement is independent and unaffected is part of the certification process and the UCAR/BFG contract.

<="" a=""> A major area of improvement as far as the air carriers are concerned is the much longer scheduled maintenance interval for the WVSS-II. The contract goal is no maintenance (recalibration) for 2+ years. The specification is for two years. The original specification for the WVSS-I was three months. A cross-section of the WVSS-II probe is provided in Figure 12.



<="" a="">

Figure 12. Cross-section of WVSS-II aspirated probe (provided by BF Goodrich Aerospace).

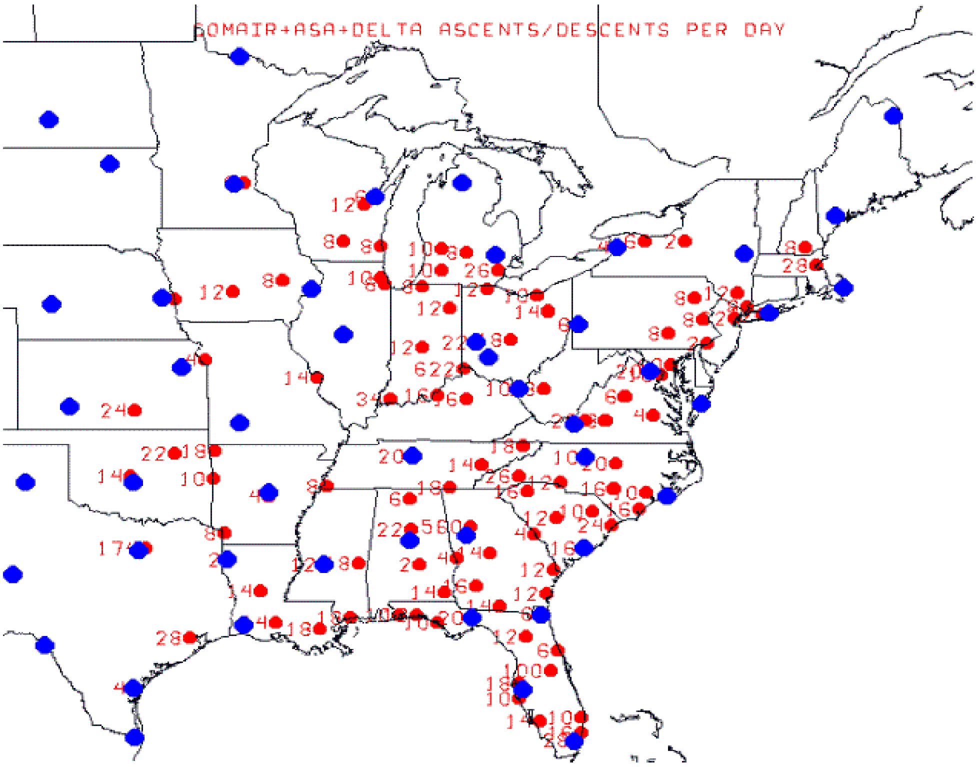
The two-year period for the WVSS-II is possible for several reasons. The sensitivity of the laser receiver, the power of the diode laser, and the sensitivity of the 2nd harmonic calculation all contribute to the fact that I_o in Beer's law can degrade from 100% down to 5% and still good answers can be achieved. Such degradation can occur from actual laser power loss or from "apparent" laser power loss due to a dirty reflector inside the probe. It is this allowable degradation that suggests that the maintenance period will be between 2+ years.

<="" a=""> 4.2 Perfect fit of the WVSS-II and Future Satellites

The emphasis on water vapor here does not imply that we do not also need mesoscale temperature and wind information. The commercial aircraft do also provide detailed information on the vertical structure of winds and temperature during ascent and descent. The satellite systems of today, and especially those expected in the near future, can provide the horizontal and temporal coverage for temperature and water vapor as needed for the specifications in Section 2. Where the satellite fails rather dramatically is in the vertical resolution coverage. Today's satellite resolution coverage in the vertical is about 3 km.

There is a potentially powerful satellite system coming called the Geostationary Imaging Fourier Transfer Spectrometer (GIFTS) that will have 1-2 km vertical resolution capability (see earlier version of Smith, et al, 1990). If we take the better of these numbers, then the satellite will still be a factor of ten coarser in the vertical resolution than our 100-meter mesoscale specifications in the vertical. **The aircraft can meet the vertical resolution of 100 meters (even 50 meters) but can only achieve about 200 km resolution in the horizontal (more on this below). GIFTS, and another NOAA satellite expected in the 2010 time period can be expected to provide an effective 10 km resolution of satellite profiles at a frequency of 30 minutes on the regional scale**.

Figure 13 shows the coverage from the commercial aircraft system in a rectangular region in the eastern half of the country from just one major carrier and two of its subsidiary regional carriers. This coverage approaches 200 km horizontal resolution, an average sounding frequency of 8 per day, and vertical resolution of 100 m--with one important caveat, little temporal coverage is available from those passenger aircraft from about midnight to 7 a.m. However, when one adds all major carriers and all regional carriers, including the nighttime package carriers, one can approach these above values in most of the continental U.S. except the sparsely populated regions of the West, which have fewer airports.



<="" a="">

Figure 13. Example of potential aircraft coverage from three carries (Delta, COMAIR, and Atlantic Southeast) if they all had ARINC 620 ascent/descent profiles implemented for winds, temperature, and water vapor.

<="" a=""> **Blending the tremendous horizontal and temporal coverage of future satellites with the coverage of the commercial aircraft fleet provides a near-perfect fit of observing systems for the mesoscale**. This blending is still not a strict full matrix of space/time coverage that fulfills all the specifications of Section 2. However, through the use of 3-dimensional and 4-dimensional variational analysis techniques, the models themselves help blend the data sources into a 4-dimensional picture of the mesoscale. Yes, there are still the model limitations and observational gaps. An efficient wind profiling system that is both reliable and available at reasonable cost is not here yet. However, there will be better satellite cloud drift and water vapor drift winds at higher altitudes and radar-based winds in low altitudes. The GIFTS does not provide coverage below significant cloud layers. The commercial aircraft system can provide this data (winds, temperature, and water vapor) below the cloud layers--but only at 200 km horizontal coverage east of the Missouri River.

As indicated in Section 1, there are additional ground-based systems that can emerge when the time is right to complete the composite upper air observing system. **In the interim, this plan puts forward a significant incremental improvement, which when taken together with the future satellite systems, offers a significant test bed with which to help optimize the evaluation of further incremental improvements**.

5. ROADMAP FOR IMPLEMENTATION

An executive overview of the implementation of a national operational commercial aircraft water vapor sensing system can be summarized in a few sentences. There is an evaluation of the WVSS-I in progress. Our plan includes a parallel evaluation of the WVSS-II. Purchasing, installing, and maintaining the WVSS-II units may be via an existing UCAR contract for the off-the-shelf BFG WVSS-II product. A NWS decision could be made in FY '04 whether to continue to purchase more WVSS-II units via this contract or to release a competitive RFP for another system. The FAA's Aviation Weather Research Program (AWRP) and NOAA's Office of Global Programs (OGP) have been and will continue to fund the evaluation program. Management of the program will continue through UCAR (funded by the FAA and NOAA/OGP) until such time as the NWS begins to provide significant funds for the program. This is expected in FY '03. There is a place card for the NASA Aviation Safety Program to assist in this plan and derive benefit from it (see Section 5.8).

The various phases of implementation are described in the following chronological steps (there is of course some time overlap in these steps). Section 5.1 discusses the different aircraft types, the choice of the order of certification of those types, and who will be responsible for that certification. Section 5.2 indicates the initial mechanism for purchasing the WVSS-II units for the carriers (no carrier will be required to pay for purchase, installation, or maintenance). Section 5.3 establishes maintenance procedures for the carrier and for the WVSS-II provider. This is a turnkey effort with no additional NWS personnel required.

Section 5.5 summarizes the various communication issues and details. Section 5.6 suggests two types of quality control--immediate real-time quality control at the NWS and a longer-term monthly quality control effort by UCAR. Section 5.7 (Evaluation and Forecast

Improvement) lists the various organizations and special interest groups that will both use and evaluate the WVSS-II data. Section 5.8 does not fit this chronology but discusses how NASA could interact with this plan in a synergistic way to benefit all agencies and the country as a whole.

5.1 Certification of Aircraft Types

The first certified aircraft type was the B-757, which represented a relatively modern jet with sophisticated avionics. These aircraft are primarily used within the USA mainland, and provided a large number of ascents and descents per day. UPS and American Airlines are currently flying the WVSS-I on their B-757s. The first certification aircraft for the WVSS-II will be the Delta Airlines B-757s, and immediately thereafter, the B-737s.

The FAA will take the lead in funding the certification process for the B-757 and all other aircraft types. The existing UCAR contract with BFG has contract options for the certification of virtually every major aircraft type--including the new popular regional commuter jets, Embraer and Canadian Regional Jets (CRJs). Only because of funding limitations must we proceed with a nearly serial progression in the certification of the various aircraft types. This makes the choice of which aircraft type to begin with somewhat difficult--and there are competing factors in this selection process. **However, should more funds be supplied than indicated in Section 6, then the capability exists at UCAR and BFG to accelerate this certification process**.

There are three basic varieties of TAT probes that serve virtually all of the commercial aircraft in use today. The first variety is aspirated and serves basically all Boeing aircraft except the B-727. The second variety is non-aspirated and serves the B-727, CRJs, and Embraers. The third variety is for Airbus aircraft. The first aircraft certification costs for each of these three varieties is more than the cost for subsequent aircraft certification that use that same variety because slightly different designs are required--thus more re-certification tests must be repeated.

Table 2 indicates a sample strategy of aircraft type certification. This is driven by the desire for greater horizontal spatial coverage and temporal coverage of water vapor by the use of the regional commuter jets on one hand, and the desire for international and cross-ocean coverage via B-767 aircraft on the other. Airbus aircraft also fly in the United States and the placement of Airbus aircraft at the bottom of the list is not desirable, but only practical. **It is hoped that European organizations can help fund these Airbus aircraft certifications of the WVSS-II**. UCAR will be responsible for working with one carrier for each aircraft type certified. UCAR would also assist the NWS in identifying multiple air carriers that would accept the WVSS-II for installation. Prices for obtaining the STC are already outlined in the UCAR-BFG contract.

Table 2. Expected Sequence of WVSS-II Certification by Aircraft Type

Aircraft Type	Air Carrier	Approximate Date
B-757	Delta	11/01
B-737	Delta	12/02
B-767	UPS	6/02
CRJ	COMAIR	11/02
Embraer	Continental Express	11/03
B-747	United	10/04
B-777	United	12/04
A-319	TBD	TBD
A-321	TBD	TBD
A-330	TBD	TBD

5.2 Purchasing WVSS-II Units

The UCAR contract has options for the purchase of the WVSS-II units. These prices are repeated in Table 3. The current strategy is for an early purchase of 100 units for immediate demonstration. If the WVSS-II performs close to its expectations, then it will be a clear and easy decision to continue to purchase them into the foreseeable future. The approximate "installed" price is $20,000. The lifetime of these units will be 20 years. The total maintenance cost (air carrier and BFG maintenance) will be close to $1,000 per year (see more on this subject in Section 5.4). If one also adds the MDCARS communication costs and assumes a $1,000 per year real-time communication cost per aircraft, then we have a total cost of $60,000 per aircraft for a **twenty-year period**.

Table 3. Price for WVSS-II vs. Quantity Ordered

Quantity	Price
1-5	$24,200 each
6-15	$22,000 each
16-30	$20,000 each
31-60	$18,300 each
61-100	$16,300 each

If one assumes eight profiles per day (an industry average of four ascents and four descents per day), for 325 flight days per year, for twenty years, that is 52,000 profiles at a cost of **$1.15 per profile**. This ignores the **enroute** data. Assuming 200 reports (levels) per day (ascent, descent, and enroute per aircraft), then the **cost per report is 4.6 cents**. Compare this with the true recurring cost of a radiosonde of about $150 per profile.

If, however, the WVSS-II does not perform to our expectations, then a decision will be made in FY '04 to initiate a competitive procurement for a new system. **The experience of the two demonstrations of the WVSS-I and WVSS-II will help guide the preparation of that procurement.** Table 4 indicates the expected purchases and installation for this plan, consistent with the resources requested in the NWS initiative.

Table 4. Number of WSS-II Units Purchased

Fiscal Year	FY '02	FY '03	FY '04	FY '05	FY '06
Number Purchased	14	86	120	120	120
Cumulative Number	14	100	220	340	460

5.3 Installation of the WVSS-II

Installation of equipment on commercial aircraft is invariably done by the air carrier (unless it is performed by the aircraft manufacturer). For the WVSS-I, the government paid the air carrier (UPS and American Airlines) for installation of the WVSS via a sole-source contract. The cost was broken down as follows: $6510 for Labor, $1250 for Parts, and $1000 for the DFDAU Interface, for a total of $8760. The digital flight data acquisition unit (DFDAU) interface cost is a one-time cost (paid upon installation) of $1000 that goes to the avionics vendor who has imbedded the ARINC 620 WVSS-II format into his avionics software.

The installation of the WVSS-II is trivial compared to the WVSS-I, which required a new aperture in the aircraft skin and a special doubler plate for aircraft skin integrity. The labor for the WVSS-II installation will be less than one-third, and the parts less than one-half of the previous value for the WVSS-I. This makes the installation per aircraft approximately $3,700.

Installation is best performed during a scheduled C-check. This is scheduled well in advance by the air carriers. In order to get a rapid implementation of the WVSS-II, once it has been certified by the FAA for a given aircraft type, it is best to have two or three air carriers lined up to accept the WVSS-II for that aircraft type. This responsibility will be UCAR's through FY '04 and then it may shift to the NWS. This multiple installation is shown in Table 4 and in more detail in Table 5.

5.4 Maintenance–Air Carrier and WVSS-II Manufacturer

There are two types of maintenance associated with the WVSS-I and the WVSS-II. The procedures are the same, but the maintenance interval will be much longer for the WVSS-II.

The first type of maintenance is performed by the air carrier. At approximately a two-year interval (exact time to be determined by the air carrier at their convenience), the air carrier will remove the WVSS-II probe, and immediately replace it with a spare WVSS-II probe. About 10% of the units flown must be available as spares (see section 6.1). This should take less than one hour. The carrier will then ship the "used" probe to BFG. BFG will replace minor parts, recalibrate the unit, and return it to the air carrier within 30 days. Shipping of the WVSS-II probe will be paid by BFG (both ways) and the air carrier will use a pre-arranged overnight shipping account established for this purpose by BFG. **This will free the air carrier of any extra bookkeeping**.

The second kind of maintenance (at BFG) has already been described. BFG will be paid for this recalibration and any other maintenance not covered in the warranty via their contract with UCAR. After FY '04, this maintenance contract may be the responsibility of the NWS.

5.5 Real-time Communications

The subject of real-time communications, changing so fast in all segments of human activity, is best discussed as it exists today and as it might be tomorrow. The subject might also be sub-divided into formats, communication system, and organizational stability.

The original ARINC 620 specification for ascent, descent, and enroute messages downlinking winds, temperature, water vapor, and turbulence were described in Fleming (1996). This format served the UPS (AlliedSignal avionics) WVSS-I aircraft and the field downlinked was mixing ratio. The new ARINC 620 specification (Version 4) has RH as the downlinked moisture variable. This is the final format (for the foreseeable future) and serves the WVSS-I (Teledyne avionics) and the WVSS-II. A copy of this format and principles behind its use are described in Fleming (2000).

The existing MDCARS contract is quite sufficient now and will be in the future for the decoding of carrier aircraft weather-related messages (including ARINC 620 Version 4) and sending the data to the NWS and the FAA in the BUFR format. This is a 24-hour per day, 7-day per week operation. The high vertical resolution format of ARINC 620 (Version 4) is automatically used by these carriers who have the WVSS-II. This is the recommended format of NWS field office personnel (cf. Decker, et al., 1999). Efforts are underway to encourage all air carriers to adopt ARINC 620 (currently with or without the WVSS-II), but ARINC can decode any agreed upon format used by the carrier.

The original VHF ACARS was a character-based transmission system that is just beginning to get congested. The so-called "second-generation" ACARS--VHF Data Link (VDL-Mode 2) is digital-based and will offer an order of magnitude improvement in throughput. This will be available in 2002. There are a number of other aviation communication upgrades planned and several other major communication options for the future. These methods all offer greater flexibility, greater capability, and perhaps greater costs. However, the existing ARINC 620 format is very cost-conscious, and its implementation in any future communication system should serve the NWS well into the future.

The current organizational arrangement between those air carriers, allowing their weather information to reach the NWS in real-time without any formal agreement or money exchanging hands for the "downlink" communication charge, has worked extremely well and has been a win-win situation for all concerned. There are discussions underway on how to make this organizational arrangement more formal and stabilized. Our point here is that the downlink communication charges are so relatively small and the value of the data so relatively large--that **any** financial cost-sharing arrangement that might be agreed upon in the future will remain a win-win situation for all concerned.

5.6 Data Quality Control Activities

Data quality-control activity is the responsibility of the NCEP of the NWS. The ACARS winds and temperature data have been extremely good--winds better than radiosonde winds (maybe equal in accuracy after GPS sondes are introduced in 2005), and temperatures comparable to radiosondes. There are occasional instances where an individual aircraft's temperature becomes biased (bird strike, electronic failure, etc.) and the real-time quality control (q.c.) effect has picked this up. The NOAA FSL team has developed some q.c. efforts that will be passed to the NWS.

The WVSS-I aircraft have the Vaisala thin-film capacitor as the water vapor sensor (RH as a linear function of voltage). These capacitors can change their calibration over time (as seen in radiosonde cases) and an effort for long-term q.c. has begun at UCAR to monitor such changes. This effort has been able to detect a dry-bias trend over time in one aircraft. This was an aircraft that had been flying well over the intended six-month recalibration period. The subsequent replacement of a new WVSS-I probe returned the data to normal.

The WVSS-II probe should not have a bias problem over time (except when the effective I_o degrades to only 5% as described in Section 4.1). Nevertheless, this ongoing monitoring of cumulative monthly statistics of each aircraft is an important q.c. practice that is considered a part of the operational implementation of the WVSS-II and will be continued at UCAR. This monthly product will be available to the NWS as part of the real-time quality control.

5.7 Evaluation and Forecast Improvement

There are a great many scientists in government, academia, and industry who will be ecstatic to finally obtain mesoscale upper-air information from this new powerful composite system of new commercial aircraft data and new high-resolution satellite data. **For explicit improvements in the air traffic congestion problem, there are already funded elements of the FAA's Aviation Weather Research Program waiting to capitalize on such a data set**. There are a number of other non-meteorological changes that are going to be required to alleviate the future air traffic delays. However, improved weather support will most directly help the problem, and will indirectly help with the implementation of other possible solutions to relieve that congestion problem.

Coordination of anticipated weather problems and aviation flow control at the national level has begun in the FAA System Command Center that oversees the hour-to-hour operation of the U.S. Air Traffic Control System. Several organizations were behind an industry Spring 2000 plan to construct more efficient alternative traffic patterns for various weather scenarios. For a number of reasons, improvements have been very modest. Until one can predict with precision the occurrence or non-occurrence of large-scale convection, it is likely that this statistical impact will remain small. Part of this precision is predicting the precise location, intensity, and timing of MCSs. Precision in these parameters can allow national planners to have more significant impact and allow automatically designed traffic flow algorithms to work.

Another suggestion to help relieve the congestion problem is greater use of regional airports. Including more regional airports and using ACARS or another equivalent real-time communication system for the newer regional jet commuter aircraft would provide significantly more mesoscale observational coverage of the atmosphere and thus, provide direct positive feedback to the entire national airspace system (NAS).

The NWS scientists and those working on mesoscale research in NOAA's research laboratories will be using the data for improved forecasts of severe weather, precipitation, and improved flood warnings. A particular area that many agencies must and will provide resources for is the area of 3-dimensional and 4-dimensional analysis methods to optimally incorporate this improved water vapor information. Those scientists in government, academia, and industry working within the US Weather Research Program (funded by NSF, NOAA, and other agencies) will benefit from this data. There are many mesoscale weather modelers and scientists in other countries who will do research on these various socioeconomic issues using data **in this country** and data in other countries. The export of the commercial aircraft technology to other countries--in the form of sensors, formats, software, communications, etc.--is beneficial for all concerned as new discoveries, improved understanding, and better forecast techniques are shared.

5.8 Possible other Agency Linkage and Leverage

NASA is currently engaged in a national aviation **safety** program--in contrast to the FAA's goals of **safety, efficiency, and capacity**. There are several areas for mutual cooperation and these two agencies have a formal arrangement for some of these areas. In this section, we would like to stress just two points where NASA could invest in the future and help improve future operation of this composite observing network.

In Section 4.2, we showed the potential of involving the regional commuter airlines. This involvement is a part of this plan. However, NASA is also pursuing regional carriers and the general aviation community. **A major opportunity exists for NASA to invest in communication resources for those regional carriers without ACARS or to help equip those carriers with the WVSS-II or both.** This would help accelerate this operational composite observing system and also offer a better test-bed to demonstrate their new "safety initiatives". Another area for NASA participation is to allow knowledgeable oversight of the general aviation sensor development--especially with regard to water vapor sensors--as "sustained accuracy and calibration over time" is a central goal for general aviation aircraft to achieve--before their data **might** become a part of an operational composite observing system, and thus contribute to aviation safety.

The DOD does have training and transport flights that could contribute weather information to the National Airspace System, which they also use over the CONUS. They have not yet been approached, but once an off-the-shelf product (WVSS-II) is available, they will be.

Several agencies are cooperating in funding the US Weather Research Program. There are a number of field programs that could **both** use the data generated from this national water vapor plan in their respective program goals and that could contribute to the design of further incremental improvements of a better composite observing system. This interaction will inevitably lead to the identification of additional ground-based remote sensing systems like the interferometers and DIAL systems. **Studies will occur to make better synergistic use of the water vapor information from the commercial aircraft to improve satellite water vapor products.**

6. MANAGEMENT AND BUDGET

The planning and day-to-day implementation of the WVSS program thus far has been performed by UCAR with oversight by the FAA's AWRP. This management of the National Implementation Plan will shift to the NWS in FY '03 when the NWS begins major funding of the program.

6.1 Basic Plan

Table 5 shows an example of the number of WVSS-II units purchased each year and where they might be flown as part of an operational program. Table 6 shows an example of a rather conservative budget plan that would indicate total agency support for the aircraft type certification, system purchase and installation, and maintenance. This agency budget is built around the NWS initiative of major funding, which is expected to begin in FY '03.**[Please note the caveat on the first page of the Introduction concerning the budget numbers.]**

Table 5. Initial and Expected (Potential) Distribution of WVSS-II Units

	2002	2003	2004	2005	2006	Cumulative
Delta B-757	14	6				20
Delta B-737		24	30	26		80
UPS B-757		25	25	25		75
UPS B-767		12	18			30
American B-757		19	30	30	23	102

Continental Express (Embraer)			12	18	18	60
COMAIR (CRJ)			5	18	18	40
United B-737				3	40	43
Northwest B-757					21	12
Total	14	86	120	120	120	460

The budget information in Table 6 identifies who would primarily support what activity. The following discussion will cover the major categories: (i) Initial product development and subsequent aircraft type certification (primarily a FAA activity), (ii) WVSS-II unit purchases (primarily a NWS activity, but with early assistance by both OGP and the FAA), and (iii) the maintenance function (primarily a NWS activity).

(i) Aircraft type certification

The initial WVSS-II product development was funded by OGP and later by the FAA. This was via a UCAR contract with SpectraSensors who produced four prototype units for ground and flight-testing. The current UCAR contract with BFG for the off-the-shelf WVSS-II product was funded by both OGP and the FAA, with another 25% of the base contract funding provided by BFG themselves. A few notes on the dominance of BFG in the TAT probe business is provided below.

BF Goodrich (formerly Rosemont Aerospace) developed the first TAT sensor for the US military in 1956. They now supply all the TAT probes for the following aircraft: Boeing (707, 717, 727, 737, 747, 757, 767, 777), Airbus (300, 310, 318, 319, 320, 321, 330, 340), and the DC-10, MD-80, MD-90, MD-11. BFG also supplies the TAT probes for the modern jet engines built in the "west" such as Canadair, Embraer, Dornier, and Gulfstream. They also provide the TAT probes for virtually all US military aircraft and for many other military aircraft in other countries (except France and the countries of the former Soviet Union). BFG shipped over 5000 TAT probes in 2000 alone. Their customer list thus includes the top 50 major airlines and many more airlines and regional air carriers.

The initial base contract provided the WVSS-II product and included the B-757 certification. A contract option for the B-767 certification was added in FY '01. BFG also agreed to do the B-737 with their own funds in FY '01. In FY '02, another contract option will be implemented to build the off-the-shelf version of the WVSS-II applicable to the Embraer and CRJ. Certification of these aircraft and subsequent certification of other aircraft are completed with the FAA funding through FY '05. This is the last year for FAA funding for the plan as outlined here.

(ii) WVSS-II unit purchase

An initial build-up of 100 WVSS-II units is called for as part of a 16-month evaluation (October 2002 to January 2004). OGP is shown to pay for about 11 of these units for B-767 aircraft. This is a subset of the 30 B-767s that UPS will fly. These aircraft contribute data to help the air traffic concern, but also provide a global water vapor monitoring process. At the installed price of $20 K each, OGP gains some leverage here ($450 K investment shown for a $600 K value)--but recall that they provided FY '00 and FY '01 funds to complete the WVSS-II product. **Not listed in the budget of this plan are the funds of the FAA Aviation Weather Research Program that contribute to assessments and applications.**

The FAA also contributes funds to the initial WVSS-II demonstration. The NWS provides the balance of the funds for the WVSS-II purchases. A major decision could be made by the NWS in FY '04 of whether to continue to purchase the WVSS-II units from BFG (as a continuation of the operational test into actual full operations) **or** to seek a new request for proposal (RFP) for a new water vapor sensing system. As indicated in Section 5.2, if the WVSS-II performs as expected, then it will be a simple and financially efficient procedure to continue the complete buy-out through the UCAR contract. This contract already has the unit price options (shown earlier in Table 3). Moreover, this contract has **no overhead** costs for the **purchase** of the WVSS-II units. Thus, it is as if the funds (FAA and NWS) are going directly to BFG.

As part of our risk reduction plan, a RFP would be prepared and held in readiness **at that decision point** so that little time is lost. **This RFP would have the benefit of information gained from the two overlapping demonstration programs involving the WVSS-I** (March 2001-January 2003) and the WVSS-II (October 2002-January 2004).

(iii) Maintenance activity

The WVSS-I program had a major delay in the transition from the AlliedSignal avionics to the Teledyne avionics. This was a negative impact for the program, but did offer some benefits. It allowed some time for American Airlines to join the WVSS-I demonstration (also waiting for the Teledyne upgrade) and allowed some funds to be carried over. Thus, the maintenance costs for the WVSS-I demonstration are shown as already paid in FY '01. The WVSS-I spare probes have already been purchased.

The maintenance costs for the WVSS-I in FY '03 are for only four months of that fiscal year (since the WVSS-I demonstration in from March 2001 to January 2003). However, additional funds are required to remove the WVSS-I at the same time that the new WVSS-II is added to those 54 demonstration aircraft. This will be about 70 K in parts and labor. The maintenance costs for the WVSS-II will average about $1 K per aircraft per year.

The maintenance contract for the WVSS-I was a NOAA contract with BFG. The existing UCAR contract with BFG will be amended to include the maintenance function. Thus, UCAR will have a single contract with BFG--and BFG will be providing maintenance to all aircraft carriers for the WVSS-II--just as they do now for their TAT probe business. **This provides a turnkey operation for the NWS--they need not establish an expensive maintenance facility. Moreover, the routine re-calibration of the WVSS-II probe (every 2+ years) allows the "temperature component" of the probe to be recalibrated by the company responsible for its manufacture. This will improve the overall quality of the temperature data of the current MDCARS data.**

The number of spare probes needed is about 10%. This number is based upon the number of air carriers involved in flying the WVSS-II and the number of probe varieties flown by that carrier. Since the probe replacement time is approximately every two years, and then turn-around time for repair (recalibration) is less than one month, the number of spare probes required would be 1/12 of the number of WVSS-II units installed over a year for that carrier-variety. This assumes that the installations have been performed evenly over the years. However, for more carrier flexibility, we want to increase that spare probe ratio to approximately 10%. Recall that the carrier has some flexibility in the exact timing of the recalibration, and this need not be exactly at the two-year interval--thus the carrier can smooth out the monthly recalibration rate over the year. **Also note that the design of the WVSS-II is such that the existing TAT probe that it replaces can be used as a spare for the WVSS-II (without the benefit of the water vapor information). This allows the aircraft to be maintained at remote locations that always have the TAT probe available.** The spare probes are purchased at a rate of 12 per year at $10K each, beginning in FY 2003 as seen in Table 6.

TABLE 6. BUDGET FOR NATIONAL IMPLEMENTATION OF A COMMERCIAL AIRCRAFT WATER VAPOR SENSING SYSTEM

		2001	2002	2003	2004	2005	2006
FUNDING SOURCES							
FAA		400	530	530	530	530	0
NOAA/OGP		150	150	150			
NOAA/NWS		0	280	1680	2620	2740	2860
OTHER							
TOTAL		550	960	2360	3150	3270	2860
UCAR Contract: product & certification		345	318	126	253	262	0
WVSS-II unit purchases							
	FAA Purchase		50	109			
	OGP Purchase		52	150			
	NWS Purchase		192	1447	2400	2400	2400
Total purchases			294	1706	2400	2400	2400
TOTAL CONTRACT COST		345	612	1832	2653	2662	2400
WVSS - I Maintenance		pre-paid	88	99			
WVSS - II Maintenance				14	100	220	340
WVSS - II Probe spares				120	120	120	120
S&B , travel, admin, Contract overhead		205	260	295	277	268	�������� TBD
TOTAL		550	960	2360	3150	3270	2860

(iv) Costs not included

There are no MDCARS costs shown in Table 6 as this is for the water vapor sensing system only. These costs are already covered elsewhere in the NWS and FAA programs. **There are no data integration or evaluation costs for the NWS included here as these are covered by base funds elsewhere or included in the NWS initiative.** There are no NWS funds provided to UCAR for long-term quality control of the WVSS-II data. This activity is being performed on a low-key basis at UCAR with the FAA funds. The NWS will decide at a later date whether to augment this activity and/or continue it beyond the FY '05 time period when the FAA funding ceases.

6.2 Plan Options

The timing and funding profile for this plan is based upon the number one ranked initiative in the NWS (June, 2000) for the FY '03 time period. Since that time, the air traffic delays have become much worse, as indicated in the introduction.

We would hope the Office of Management and Budget or Congress could act through the Department of Commerce (DOC) or Department of Transportation (DOT) and add additional funds to address this growing air traffic problem of national concern. **This**

plan in Section 6.1 could be accelerated–both in aircraft certifications and in the number of WVSS-II units installed–if additional funds beyond those indicated in Section 6.1 were made available. Appendix 3 shows a subset of the operating fleet of the ATA carriers that was operating at the beginning of 1999. This fleet is constantly being upgraded with more modern aircraft and the latest avionics. Considerably more flexibility exists in adding more WVSS-II units than is currently planned in Table 5.

If the opposite were to occur, and fewer funds were available from the NWS or their initiative was delayed yet another year, then the FAA would continue to proceed (perhaps at a slower pace) in further certification and replacement of the WVSS-I with the WVSS-II.

Appendix 1. References

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Appendix 2. List of Figures

Figure 1. MAPS verification of analysis and of predictions of 1, 3, 6, and 12 hours into the future (valid at the same time period). Provided by Sam Benjamin.

Figure 2. Cross-section of mixing ratio versus time from measurements of a Raman scatter lidar.

Figure 3. Illustration of the mixing ratios (range of values shown in g/kg) which are prognostic variables in the National Center for Atmospheric Research mesoscale model. Original illustration courtesy of Dudhia (1989).

Figure 4a--(insert) A close-up of the Water Vapor Sensing System (WVSS) probe (3 inches extend into the atmosphere and 5 inches extend beneath the surface of the fuselage.

Figure 4b--The probe is located on the left side of the aircraft in the area of the black stripe tailward of the cockpit door. Photos courtesy of Lockheed-Martin, BF Goodrich Rosemont Aerospace, and United Parcel Service.

Figure 5. Black profiles are radiosonde profiles (temperature on the right and dewpoint on the left) and blue profiles are corresponding data from the commercial aircraft. Information provided by Wayne Feltz, University of Wisconsin, Louisville, Kentucky, September 24, 1999.

Figure 6. Black profiles are radiosonde profiles (temperature on the right and dewpoint on the left) and blue profiles are corresponding data from the commercial aircraft. Information provided by Wayne Feltz, University of Wisconsin, Louisville, Kentucky, September 25, 1999.

Figure 7. Same information as in Figures 5 and 6, but the red is the data from the University of Wisconsin interferometer (called AERI). Data from Wayne Feltz of the University of Wisconsin, Louisville, Kentucky, September 22, 1999.

Figure 8. Random error in percent of signal for the WVSS as a function of temperature and as a function of height. The height curves start at the bottom as zero height, and then each subsequent curve is 2,000 feet higher until the top curve of 30,000 ft. Mach number (M) has been effectively converted to height (Z) by $M = 0.2 + 0.61 \times (Z/30,000)$.

Figure 9. Comparison of open path diode laser with Harvard Lyman-Alpha during ER-2 flight into the lower stratosphere.

Figure 10. Initial WVSS-II flight test result on the NCAR C-130. WVSS-II data is raw data gathered at 4 Hz. Standard C-130 chilled mirror instrument data is raw data with "overshoot" and false "bottoming out" not yet removed by NCAR processing.

Figure 11. Picture of WVSS-II mounted next to open path diode laser system on NCAR C-130.

Figure 12. Cross-section of WVSS-II aspirated probe (provided by BF Goodrich Aerospace).

Figure 13. Example of potential aircraft coverage from three carries (Delta, COMAIR, and Atlantic Southeast) if they all had ARINC 620 ascent/descent profiles implemented for winds, temperature, and water vapor.

Appendix 3. Subset of Operating Fleet of Air Transport Association Airlines (12/31/98)

A/C	AA	AC	AM	AW	CA	CO	DL	FX	MX	NW	TW	UA	UP	US
A300	35							30						
A320		69		34					14	63		71		6
B-727	78					32	125	163	23	38	22	75	59	
B-737				64	44	165	86					182		203
B-747		6			4	3				41		49	16	
B-757	96	5	7	13		32	100			48	16	96	75	34
B-767	75	29	5		12		85				16	46	27	12
B-777						6						34		

CRJ		25												
DC-9		20	17			20				173	54			50
DC-10	18				10	36		75		38		24		
MD-80	260		34			69	120			8	76			31

AA--American Airline

AC--Air Canada

AM--Aeromexico

AW--America West

CA--Canadian Air

CO--Continental

DL--Delta

FX--Federal Express

MX--Mexicana

NW--Northwest

TW--TWA

UA--United Airlines

UP--UPS

US--US Airways