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Tropospheric Airborne Meteorological Data Reporting (TAMDAR) Sensor Development

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ABSTRACT

In response to recommendations from the National Aviation Weather Program Council, the National Aeronautics and Space Administration (NASA) is working with industry to develop an electronic pilot reporting capability for small aircraft. This paper describes the Tropospheric Airborne Meteorological Data Reporting (TAMDAR) sensor development effort. NASA is working with industry to develop a sensor capable of measuring temperature, relative humidity, magnetic heading, pressure, icing, and average turbulence energy dissipation. Users of the data include National Centers for Environmental Prediction (NCEP) forecast modelers, air traffic controllers, flight service stations, airline operation centers, and pilots. Preliminary results from flight tests are presented.

INTRODUCTION

One of the recommendations of the National Aviation Weather Program Council was to expand and institutionalize the generation, dissemination, and use of automated pilot reports (PIREPS) to the full spectrum of the aviation community, including general aviation. In response to this and other similar recommendations, NASA initiated cooperative research with industry into the development of an electronic pilot reporting capability for small aircraft.

The ultimate goal is to develop a small low-cost sensor, collect useful meteorological data, downlink the data in near real time, and use the data to improve weather forecasts. The TAMDAR system is intended to make observations below 25,000 ft. The envisioned system will be similar to the Meteorological Data Collection and Reporting System (MDCRS) in use on commercial transport aircraft. The ultimate users of the data are NCEP forecast modelers. Other users include air traffic controllers, flight service stations, airline weather centers, and pilots. Strategies for filtering the data for each user group is an area of active research and is not addressed here.

NASA is working with Optical Detection Systems (ODS) of Rapid City, SD to develop the sensor. The sensor, currently in its second version, is capable of measuring temperature, relative humidity, magnetic heading, pressure, icing, and average turbulence energy dissipation. It can compute pressure altitude, indicated air speed, true air speed, peak turbulence, ice accretion rate, winds, and turbulence scale.

NASA is currently supporting TAMDAR research and development through coordinated efforts with the FAA and NOAA and through cooperative research efforts with industry. The overall purpose of the project is to create a system for TAMDAR, of developing a low-cost sensor and the necessary datalink for collecting weather conditions from aircraft. This system would likely utilize an existing communications infrastructure. The weather data will be disseminated and used to improve aviation safety by providing pilots with enhanced weather situational awareness. In addition, the data will be used to improve the accuracy and timeliness of weather forecasts.

Most of the moisture and convective activity are at altitudes of 25,000 feet and below, well below jet transport cruise altitudes. Other than rawinsondes, there are no other in situ observations routinely collected in this region of the atmosphere. Therefore, there is a desire to gain more meteorological observations of conditions below 25,000 feet. It has been proposed that regional airlines, package carriers, and business aircraft be equipped to report these data. Other aircraft such as general aviation (GA) airplanes may provide additional coverage.

RELATED ACTIVITIES

PIREPS - For a majority of these targeted aircraft typical operations occur in the middle and lower troposphere or below 25,000 feet (above mean sea level), where most hazardous flight weather conditions are found. To date, however, these aircraft have not been equipped for measurement and reporting of conditions aloft, except by manual voice reporting by pilots. These voice reports are infrequent and subjective. Typically, when conditions are the worst, the pilot has the least time to add condition reporting to other conduct-of-flight responsibilities. In addition, pilots tend not to issue null reports during good

conditions, even though these are just as important. The TAMDAR observations will be a supplement to, not a replacement for, pilot reports.

PAST RESEARCH - Numerous research efforts are reported in the literature regarding development of a single sensor to make meteorological measurements from aircraft. For example, one effort is described for turbulence and temperature measurements [1], while another addresses new applications for non-standard sensors [2]. New sensors are being developed, for example a new thermometer [3]. The type of airborne platform also varies. Unmanned aerial vehicles are used in numerous meteorological experiments. [4] Other studies have examined various datalinks for automating pilot reports including the use of helicopters at the 1996 Olympics [5]. In addition, there is significant research involving the impact of airborne observations on forecasts, for example local forecasts [6], and on model forecasts [7].

OTHER TERMS - The term “EPIREP” has been used by some to refer to automated electronic pilot report. The weather data are collected and transmitted automatically by aircraft systems without any pilot intervention. Since EPIREP infers some pilot interaction, that term will now be used to refer to any system that provides assistance to the pilot in collecting or transmitting traditional pilot reports. Another term that has been used is “AUTOMET.” This term is defined in a Radio Technical Commission for Aeronautics (RTCA) standard that specifies message formats [8]. Only encoding and decoding rules for the message format and not operational requirements are specified. In that standard, another term is “HAZMET.”

MDCRS - Many commercial transport aircraft are currently equipped with the Aircraft Communications Addressing and Reporting System (ACARS) for sending various aircraft data to operations centers. A subset of the collected data is MDCRS, where temperature and wind information are collected during all phases of flight [9]. Due to the nature of jet transport operations, the majority of data are reported at high altitude cruise. These data are very useful to meteorologists as commercial transport aircraft take off and land, thereby collecting “sounding” data. Currently, the MDCRS data are being ingested into the NCEP models. During cruise, these aircraft are typically at 30,000 feet and higher, well above most weather. A future implementation of TAMDAR is envisioned to be similar to the MDCRS program.

WVSS – MDCRS data does not include humidity measurements. To solve this problem, a new sensor is under development known as the Water Vapor Sensing System (WVSS) [10]. An earlier version of this probe measured only water vapor, but the current version measures air temperature and water vapor mixing ratio. A limited number of ACARS-equipped aircraft are currently flight-testing this new probe, envisioned for commercial transport aircraft.

RAWINSONDES - Currently, the measurement of humidity is the crucial element missing from MDCRS. A weather observing system that does measure humidity is the rawinsonde or weather balloon. Rawinsondes are sent up twice a day at about 90 locations around the U.S. These soundings provide excellent weather measurements from the surface to above 50,000 feet. Both MDCRS and rawinsonde data are currently ingested into the weather forecast computer models at NOAA NCEP, and in particular the Rapid Update Cycle (RUC) model. As with PIREPS, TAMDAR is not intended to be a replacement for rawinsondes.

TAMDAR CONCEPT

To avoid confusion with these and other terms, NASA has chosen to refer to its sensor as TAMDAR. The proposed airborne weather reporting system will utilize instrumented aircraft in flight as weather observing platforms that report in situ conditions to users of that information. These users include weather forecasters, weather briefers, air traffic controllers, and other pilots. The information will be transmitted or relayed to the ground as a digital data stream for collection and dissemination. The concept calls for aircraft that fly in the troposphere to be equipped with a sensor suite or package. As shown in Figure 1 in Appendix A, the TAMDAR sensor will measure weather data and compute additional values. This information will be down linked to a network of ground-based transceivers or a satellite-based network. A central processing site will collect the data, process it, and send it to NCEP, Aviation Weather Center, Flight Service Stations, airline weather centers and other sites. At NCEP, modelers will incorporate the raw data into the RUC forecast model to enhance model output. Other users will use the raw data and perform further processing to create new weather information products. A central processing site will collect all the weather products and send relevant pieces to the network of ground-based transceivers. As part of the AWIN system concept, the weather information will be uplinked back to each aircraft. The two FAA contracted providers, ARNAV and Honeywell, are currently implementing this service for Flight Information Services (FIS). An alternate routing would have the hazardous type information or HAZMET bypass the central processing site and relay directly back up to other aircraft. This concept would require a significant communications infrastructure among the various corporate and government entities.

BENEFITS OF TAMDAR - The benefits of implementing a TAMDAR system in the CONUS are listed below:

- Provide in situ weather measurements to models for improved weather forecasting
- Provide in situ observations for weather forecasters and flight service stations
- Provide regular reporting of all weather conditions

- Provide information to GA (and Regional Pilots) not currently available (e.g. Icing)
- Eliminate subjectivity in pilot reporting and null reporting
- Complement PIREPs with measurements made automatically
- Improves situational awareness related to weather

THREE ELEMENTS

Electronic pilot reporting needs to be developed using a systems approach to ensure commercially viable implementation. As shown in Figure 2, TAMDAR has three elements that are key to implementation: Coverage, Cost, and Capability.

COVERAGE – Weather observations are needed on a regular basis if users are to be able to depend upon the availability of the resulting enhanced reporting and forecasting capabilities. Thus, the first step is to determine which aircraft to equip. The answer to this question depends upon an understanding of the airspace that needs to be sampled and the frequency with which it needs to be sampled, i.e. the coverage that the equipped airplanes would provide. As a group, the TAMDAR-equipped aircraft should provide observations: spanning the entire United States; at altitudes of 25,000 feet and below; seven days a week; both day and night; in both VMC and IMC; and throughout all four seasons. An airplane that is operated for flight training in day VMC would be of limited use, as would be an airplane that is operated sporadically or that is not operated in northern states during the winter. IMC-capable aircraft that are operated over defined routes on a regular basis appear to be the best candidates for TAMDAR equipage. Thus, regional commuter airlines and package carriers should be the first implementers followed by the GA community at large.

The FAA tracks and archives all IFR flights in the CONUS and refers to its database as the ETMS, or Enhanced Traffic Management System. Using this database, an analysis was performed to determine if there is sufficient coverage. Figure 3 shows the number of daily TAMDAR-eligible flights averaged over each week for three different user classes. TAMDAR-eligible flights are defined as “GA,” or Part 91, “air taxi” or Part 135, and “other.” The “other” group consists of government, military, and emergency aircraft that are not counted in the first two groups in the ETMS database. Positions are reported every four minutes and are accurate to 1 minute of latitude and longitude. For the analysis, a 1-degree latitude/longitude grid was used. The total number of these flights was calculated during each Greenwich Mean Time (GMT) day from April 1999 to March 2000. The number of average weekly TAMDAR flights ranged from about 11,300 to 18,500 flights per day. From April 1999 to November 1999, the count of TAMDAR-eligible flights fluctuated between 15,000 and 18,000. During the holiday season, late-November 1999 through January 2000, the total operations tend towards lower numbers (e.g., as low as 11,300 average flights per day). A spatial analysis (latitude/longitude) of the combined eligible flights at six different altitude bands and for four different weeks (seasonal) was also performed. The particular weeks selected were typical of the data for each season. The plot shown in Figure 4 is from this analysis, and is an estimate of the percent coverage of the CONUS by the combined TAMDAR-eligible flights.

COST – Once the aircraft that provide the needed coverage have been identified, an acceptable cost of this capability needs to be established. This involves elements of business modeling to determine such parameters as cost of data collection, messaging, processing and dissemination; cost of sensor and data link installation, approval, upkeep, periodic calibration, and replacement; and cost of packaging requirements to induce equipage and/or fleet deployment. The development of a second-generation airborne system based on those parameters that can lead to commercialization of TAMDAR is also desired. The incentives for aircraft owners to equip their aircraft for TAMDAR need to be weighed against the costs involved. Finally, the need for incentives to implement and operate a system of electronic pilot reporting should be addressed. It is not unreasonable to envision the operator of a TAMDAR-equipped aircraft selling the meteorological observations to the users. A goal would be to develop a workable strategy for achieving deployment and implementation of TAMDAR on a large scale within the National Airspace System (NAS).

With support from NASA and the FAA, the Old Dominion University Department of Engineering Management feasibility study was conducted to address these cost issues [11]. Some results from the study include:

- Financial intervention by the government will be needed for NAS-wide implementation
- Infrastructure costs are about $14.8M nonrecurring and about $2.9M/yr in recurring
- Savings are numerous, for instance, improvements in NAS delay amount to $13M in present value
- An incentive based policy should be used to motivate participation
- Regional airlines and package carriers are the most likely candidates for equipage
- Weather information providers foresee a great market potential to enhance development of local forecast models
- An additional 160,000 data points per day could be collected nationally from 1000 regional airline and 500 package carrier aircraft

CAPABILITY - The third element involves the development of cost effective TAMDAR sensor and data transmission systems for target aircraft. A measurements list that includes the parameters, ranges, resolution and accuracy desired has been jointly

developed by NASA, the FAA and NOAA and is shown in Table 1 in Appendix B. [12] This list is based on those input data to forecast tools that would have the greatest beneficial impact on the products produced. While most parameters have specified values, some are suggested values. Also, the "T" refers to "threshold" or the minimum capability and "O" refers to "objective" or the desired performance as specified by the meteorological users. In addition, a strategy for how to report the data has been developed based on the ACARS model. This minimum reporting strategy is listed in Table 2, also in Appendix B.

TAMDAR PROJECT

A flowchart of planned efforts related to TAMDAR is shown in Figure 5. The flowchart begins with the TAMDAR Data Users, as shown in the upper left-hand corner. Their measurement requirements and alternative methods define a system concept. This leads to system architecture with inputs from current standards. The communications and ground infrastructure efforts (shaded boxes) are to be performed by WINCOMM and FAA. The sensor requirements were developed based on the cost, coverage, and capabilities related efforts. A prototype sensor is currently being tested both in ground facilities and in flight tests. The entire process will repeat after the system performance and benefits to users have been assessed. This process will result in another version of the sensor that will be used for the final phase of development – a fleet operational evaluation. AWIN intends to complete the development to an acceptable level of technology readiness.

SENSOR DESCRIPTION **–** The TAMDAR sensor is intended for commercial applications and yet affordable for smaller aircraft as well. The airborne sensor package currently under development provides indicated airspeed, pressure altitude, eddy dissipation rate, air temperature, relative humidity, and ice detection. A photograph of the probe portion of the TAMDAR sensor is shown in Figure 6. This external zero-lift airfoil probe extends beyond the aircraft skin by about four inches. An internal electronics module has dimensions 3 inches by 3 inches by 4 inches. The probe and electronics module are directly connected. Together, these two components are mounted at a single location on either the wing or fuselage. This second or current version of the sensor has an approximate weight of 1.5 lbs., and aerodynamic drag of 0.4 lb. at 200 knots. The power consumption with de-icing heaters powered off is 10 W, and with heaters on 280 W. Listed in Table 3 are the specifications for measured parameters, while Table 4 lists specifications for derived or computed parameters. An airborne system configuration for the TAMDAR sensor is shown in Figure 7. In the figure, the sensor (mounted under a wing) is connected to a Heading and Accelerometer/Attitude Module, an optional cockpit annunciator for icing, a GPS receiver, and a data link transceiver.

Relative Humidity - The second version of the TAMDAR sensor uses thin-film (polymer) capacitors to measure relative humidity. Capacitor saturation has been identified as a source of temporary loss of data. In addition, this type of device may lose its calibration over time due to degradation of the polymer. Testing will be performed to ascertain the degree of risk associated with the use of this technology. An additional long-term stability test is being conducted using a new technology humidity sensor. This MEMS-based sensor is being subjected to ambient environmental conditions and calibrated on a monthly basis. The calibration data will be used to track the long-term stability. If this new technology proves to be viable, then the MEMS-based humidity sensor will replace the capacitive humidity sensor in the third and final version.

Airspeed and Winds - Measurements from both pitot and static pressure ports and an ambient air temperature sensor (compensated for Mach heating), are used to calculate true and indicated airspeed and pressure altitude. The true airspeed, combined with inputs from an external GPS and external Heading and Acceleration/Attitude Module enable the sensor to calculate wind speed and direction.

Turbulence – Several approaches are available to quantify turbulence. [13] These metrics include maximum or peak vertical acceleration, root-mean-square vertical acceleration, discrete gust load, and eddy dissipation rate. Development of the TAMDAR sensor includes a comparison of both acceleration-based and eddy dissipation rate methods. Input from an external Heading Accelerometer/ Attitude Module could also be used to quantify turbulence-induced acceleration experienced by the specific aircraft. The McCready method computes eddy dissipation rate from an analysis of pressure fluctuations. [14] A preferred approach, this method promises a non-aircraft specific estimate of turbulence and turbulence severity. After further investigation into these two main methods, one will be chosen for the third or final version of the TAMDAR sensor.

Data Reporting - Based upon static pressure and derived pressure altitude, the sensor can determine the flight mode: ascending, enroute, or descending. The intervals at which data are collected, buffered, and transmitted are controlled based upon flight mode. Typically, atmospheric data are buffered at six-second intervals during ascent, three-minute intervals while enroute, and one-minute intervals during descent. These intervals can be adjusted by a ground to air command. Configuration data are stored internally to save communications costs. The CPU in the transceiver packets the sensor output, along with other messages, in an ACARS compatible format for transmission to the ground and the ARINC network.

PROTOTYPE TESTING

The first and second versions of the sensor have been tested in ground-based facilities and in flight tests. All prototype testing is scheduled to end in Summer 2002. A final version will be certified for use in a fleet operational

evaluation tentatively scheduled for 2004. The third and final version will be produced for certification testing and for an operational evaluation.

GROUND TESTING – The initial version of the sensor was tested in facilities at NASA Langley Research Center. The tests were conducted according to RTCA DO-160D specifications. In particular, high temperature, low temperature, low pressure (high altitude), vibration, and wind tunnel tests were performed. Significant design changes have occurred since the initial version as a result of these ground-based tests. The current version has been tested in a wind tunnel at the ODS facility. No additional ground-based testing is anticipated for the current version of the sensor.

The initial version of the sensor was also tested at the Icing Research Wind Tunnel (IRT) located at Glenn Research Center, Cleveland, Ohio. Further testing will be conducted at the Cox Icing Wind Tunnel in New York City scheduled for Summer 2002.

FLIGHT TESTING - The goal of all flight tests is to validate the accuracies of each of the sensor measurements. In addition, of interest is the operational envelop of the sensor. The current version of the sensor was tested on-board the NASA Glenn Research Center Twin Otter, an instrumented aircraft used in icing research. The sensor is shown mounted under the wing of the Twin Otter in Figure 8. For these test flights, the sensor data can be compared to measurements from onboard instruments. ODS is also performing test flights using a Beech Bonanza and will perform a rawinsonde following experiment. This test flight is currently scheduled for Summer 2002.

Citation II - The University of North Dakota Cessna Citation II research aircraft has been performing test flights with the sensor. This aircraft is instrumented to perform cloud physics and other atmospheric research. These instruments provide a calibrated reference for TAMDAR sensor measurements. Figure 9 is a photograph of the sensor mounted on the nose of the Cessna Citation II. For reference temperature and pressure, Rosemount sensors are used. For dew point temperature, the Citation is instrumented with an EG&G Cooled Mirror. As the TAMDAR sensor is still under development, these data are preliminary. Some developmental results for a test flight that occurred on February 2, 2002 are shown in Figure 10 through Figure 16. Dedicated flights are currently scheduled for Summer 2002.

Preliminary Results - Figure 10 compares ambient air temperature measurements of the TAMDAR sensor with the Citation Rosemount temperature sensor. Note the large heating spike at about 2600 seconds into the data file where the de-icing heaters are melting the external ice. A comparison plot of pressure altitude is shown in Figure 11. Relative humidity is measured with a chilled mirror on the Citation. The cycling of this sensor can be seen in the comparison plot in Figure 13. Also shown in this figure is the TAMDAR sensor relative humidity measurement. True airspeed is plotted in Figure 14 and indicated airspeed is plotted in Figure 15. These two plots show a very good correlation between the sensors. Further analysis is needed to determine error sources. Ice warning as measured by the TAMDAR sensor and the Citation liquid water content (LWC) probe is plotted in Figure 16. Note that the TAMDAR sensor measures ice accretion and issues ice detection as soon as it exceeds the 0.03 inches threshold. The previous plot of ambient temperature shows a large temperature spike at the same time. During de-icing, all sensor measurements are not reported. The “data quality flag” in Table 1 is used to indicate this temporary condition. The TAMDAR computed value for eddy dissipation rate is plotted against the Citation value in Figure 17. An eddy dissipation rate value can be correlated to a specific value on any of the published turbulence scale values.

Although a significant number of flight tests are still needed, these preliminary results show fairly good agreement with the reference measurements. Additional flights on the Citation II are scheduled at a range of altitudes and meteorological conditions.

FUTURE IMPLEMENTATION

A vision of a future implementation of TAMDAR is shown in Figure 18. An automated system for collecting and disseminating meteorological information includes air-to-ground and air-to-air data links, ground-based communications architecture, and a majority of the targeted aircraft equipped with the sensor. In order to make TAMDAR an operational system that contributes to the overall safety of aviation and to the improvement of weather forecasts, several implementation issues must be addressed. Infrastructure and maintenance costs based on an overall business strategy are necessary. A situation that will require changes to FAA regulations is a TAMDAR-equipped aircraft reporting ice but not being rated to fly in known icing conditions. Other changes to regulations include aircraft manual changes, pilot training, owner or operator installation and maintenance. A fleet operational evaluation is planned to address some of these issues.

SUMMARY

The NASA Aviation Safety Program's Aviation Weather Information element is currently supporting TAMDAR research and development through cooperative research efforts with Georgia Tech Research Institute and Optical Detection Systems. The project has developed a prototype sensor that has been tested in ground facilities and is currently being flight-tested on three different aircraft. Both a feasibility study and a coverage study were conducted and support the overall concept of a TAMDAR-like system in the NAS. Based upon these studies, regional airline and package carrier (turbo-prop) aircraft are being targeted for an operational evaluation scheduled to occur in 2004. Work will continue to

demonstrate an operational ground reception and processing network, conduct operational evaluations with equipped aircraft, and demonstrate the capability for re-dissemination of data to users such as Flight Service Stations and the National Weather Service. The goal of this project is to improve aviation safety by providing pilots with enhanced weather situational awareness. In addition, the data will be used to improve the accuracy of weather forecasts.

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

A/C: Aircraft

ACARS: Aircraft Communications and Reporting System

ARINC: Aeronautical Radio Incorporated

AUTOMET: Automated Meteorological Transmission

AWC: Aviation Weather Center

AWIN: Aviation Weather Information

CONUS: Continental United States

CPU: Central Processing Unit

EPIREP: Electronic Pilot Report

ETMS: Enhance Traffic Management System

FIS: Flight Information System

FAA: Federal Aviation Administration

FSS: Flight Service Service

FSL: Forecast Systems Laboratory

GA: General Aviation

GMT: Greenwich Mean Time

GPS: Global Positioning System

GTRI: Georgia Tech Research Institute

HAZMET: Hazardous Meteorological Report

IFR: Instrument Flight Rules

IMC: Instrument Meteorological Condition

IRT: Icing Research Tunnel

M: Million

MDCRS: Meteorological Data Collection and Reporting System

MEMS: Micro-Electro-Mechanical System

MFD: Multi-Function Display

NAS: National Airspace System

NASA: National Aeronautics and Space Administration

NCEP: National Centers for Environmental Prediction

NOAA: National Oceanographic and Atmospheric Adminstration

NWS: National Weather Service

O: Objective

ODS: Optical Detection Systems

ODU: Old Dominion University

PIREP: Pilot Report

RTCA: Radio Technical Commission for Aeronautics

RUC: Rapid Update Cycle

T: Threshold

UND: University of North Dakota

VMC: Visual Meteorological Condition

VFR: Visual Flight Rules

VFH: Very High Frequency

W: Watt

WINCOMM: Weather Information Communication

WVSS: Water Vapor Sensing System

WxAP: Weather Accident Prevention

APPENDIX A

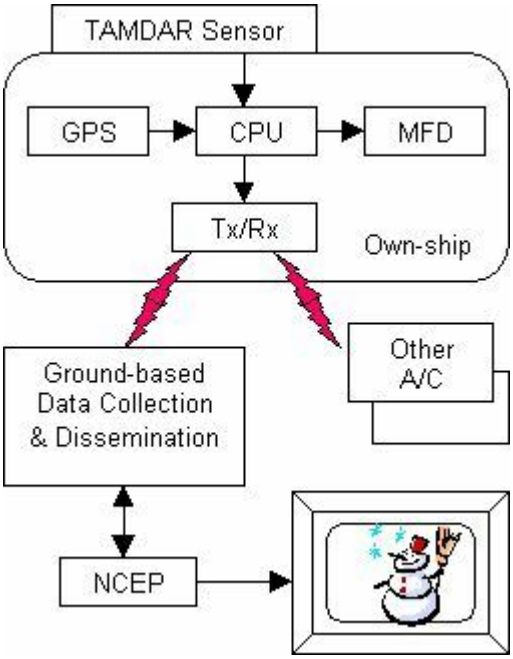

Figure 1. CONUS TAMDAR Concept

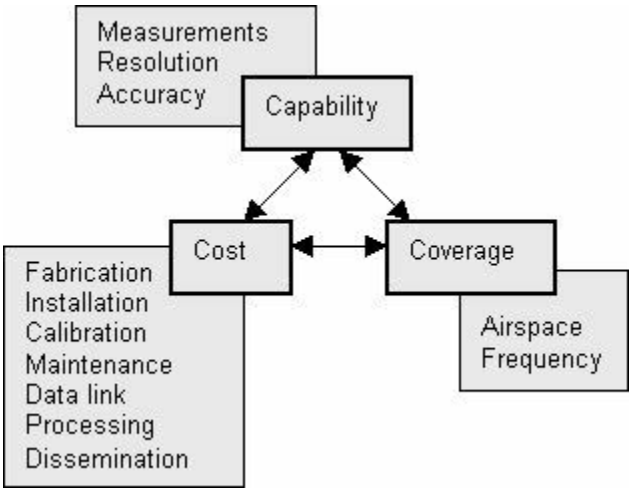

Figure 2. Initial Development Strategy

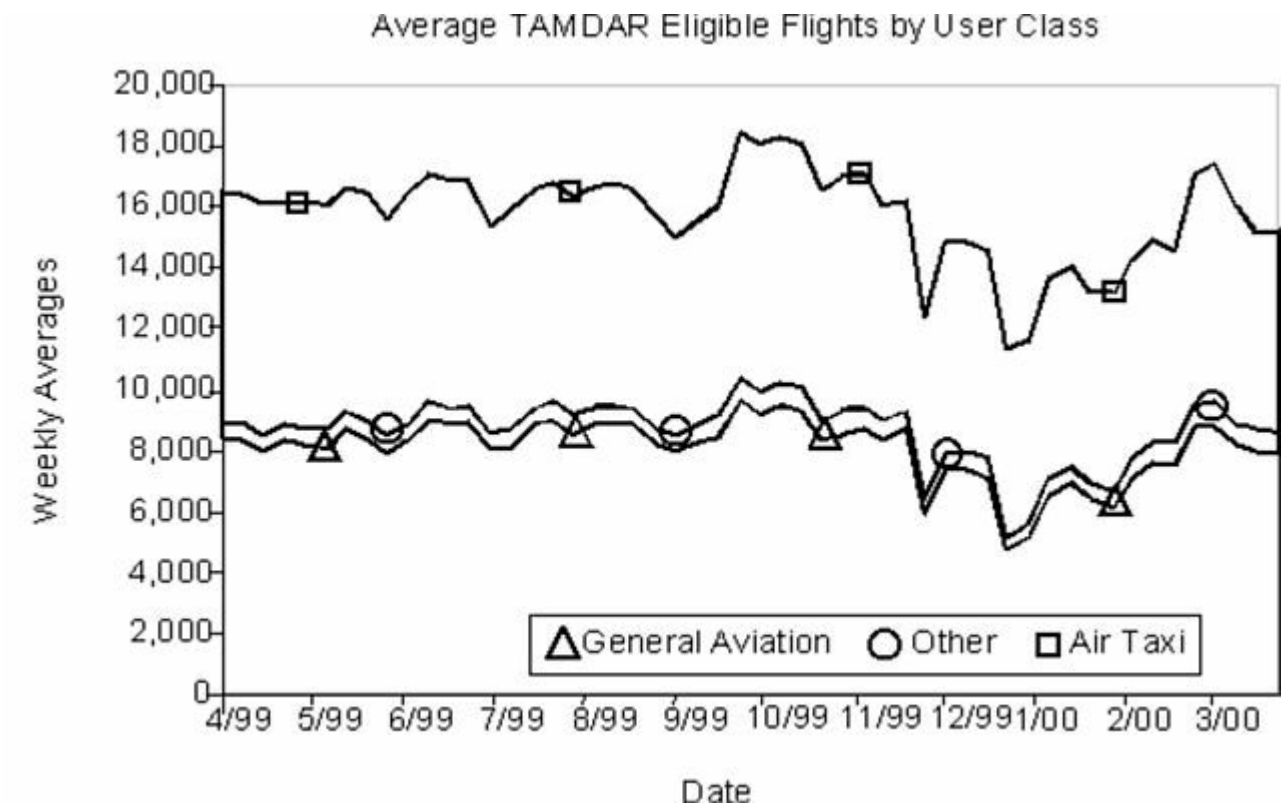

Figure 3. Weekly averages from ETMS analysis

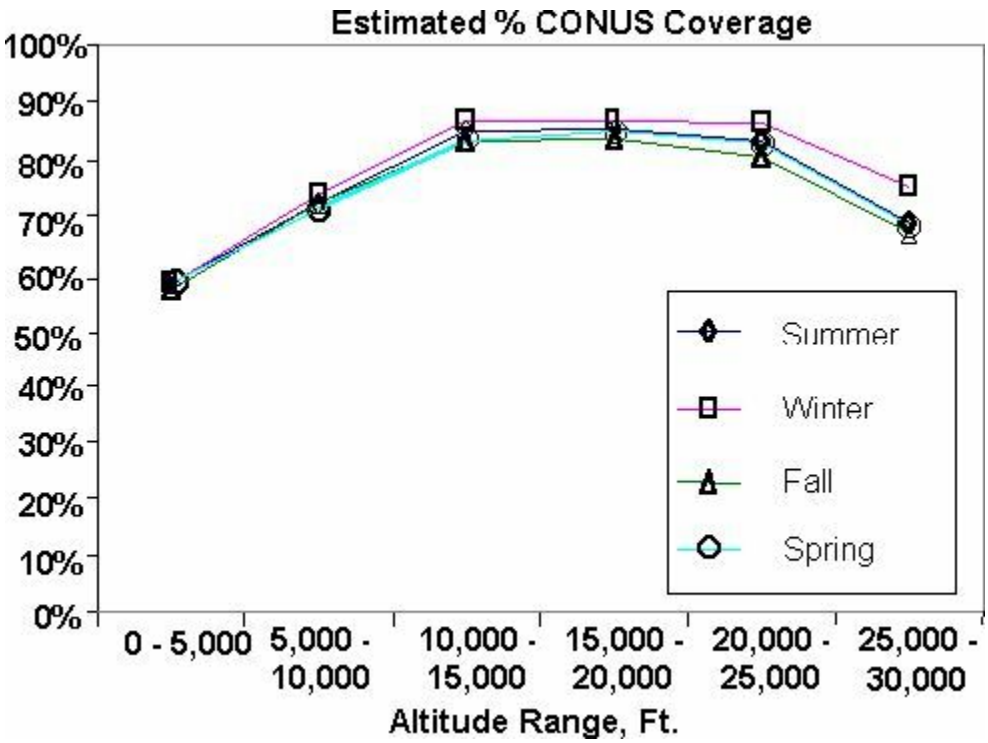

Figure 4. Summary of Spatial Analysis

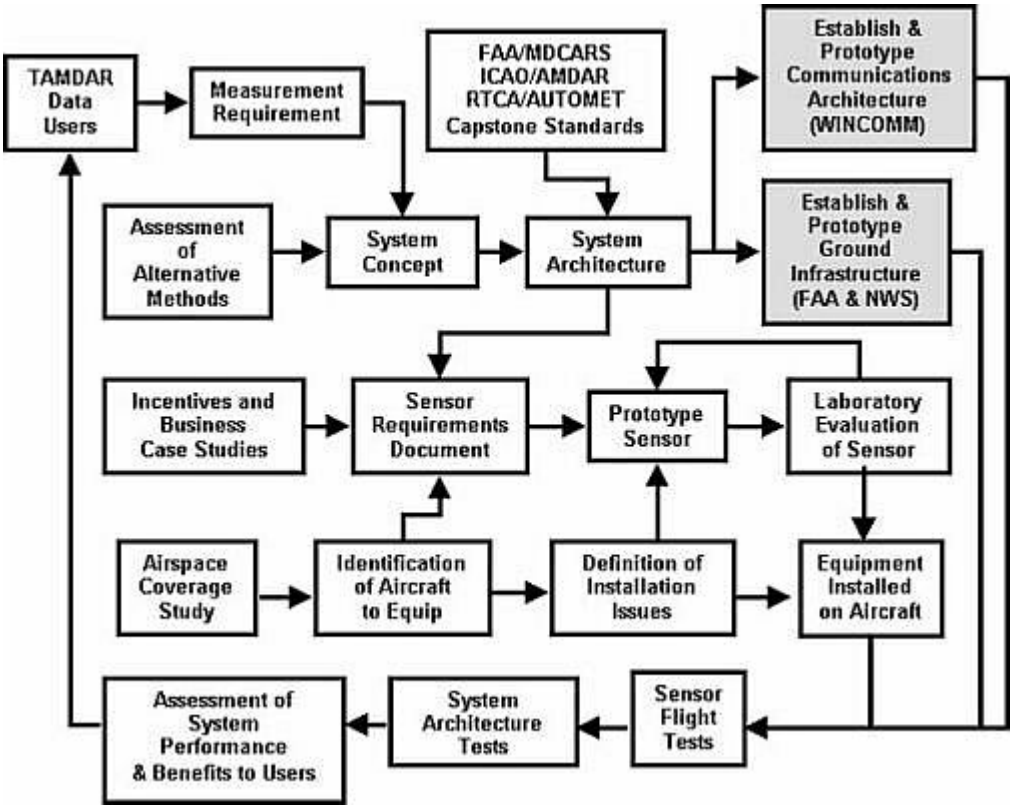

Figure 5. TAMDAR Development Flowchart

Figure 6. Current version of the TAMDAR Sensor

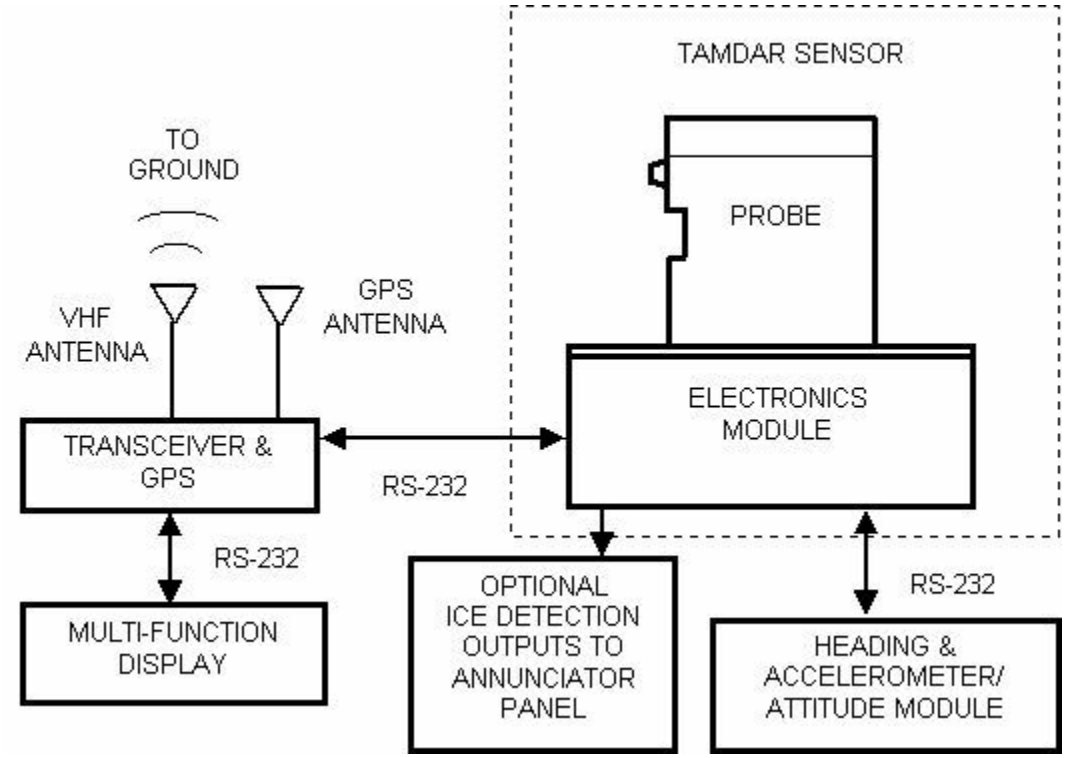

Figure 7. TAMDAR Airborne System Configuration

Figure 8. Photograph of TAMDAR installed under wing of NASA Glenn Twin Otter

Figure 9. Photograph of TAMDAR sensor (at upper right) installed on nose of UND Cessna Citation II

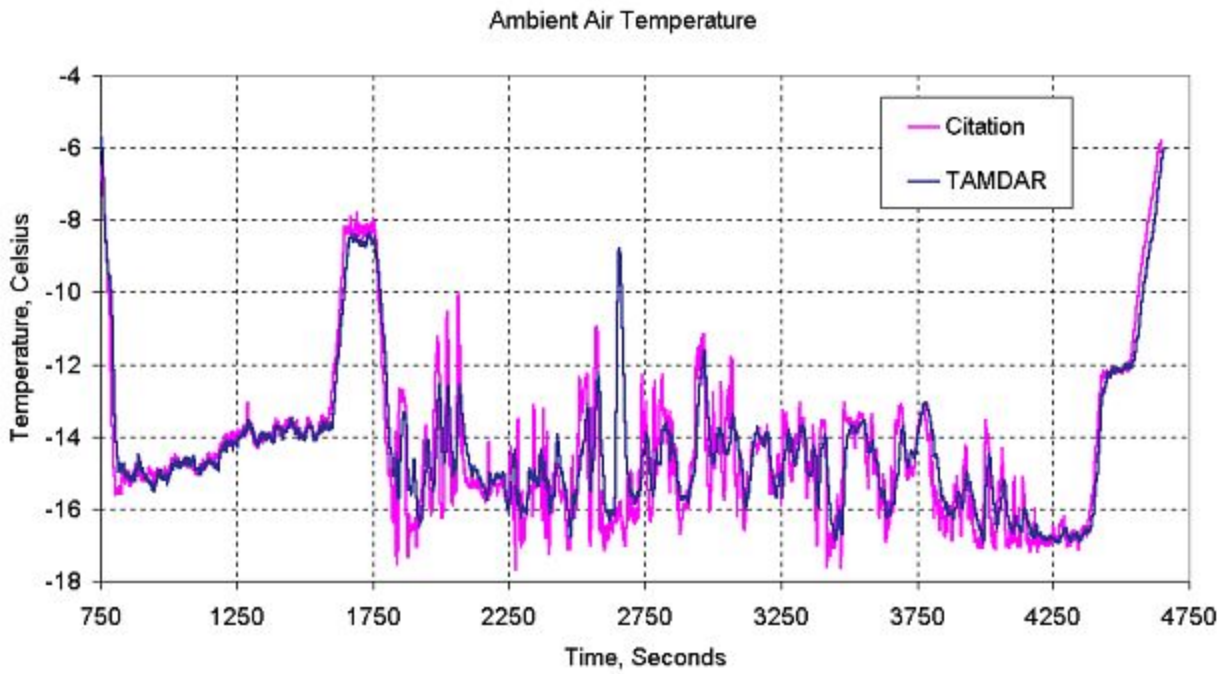

Figure 10. Comparison of ambient air temperature from UND Cessna Citation II and TAMDAR sensor

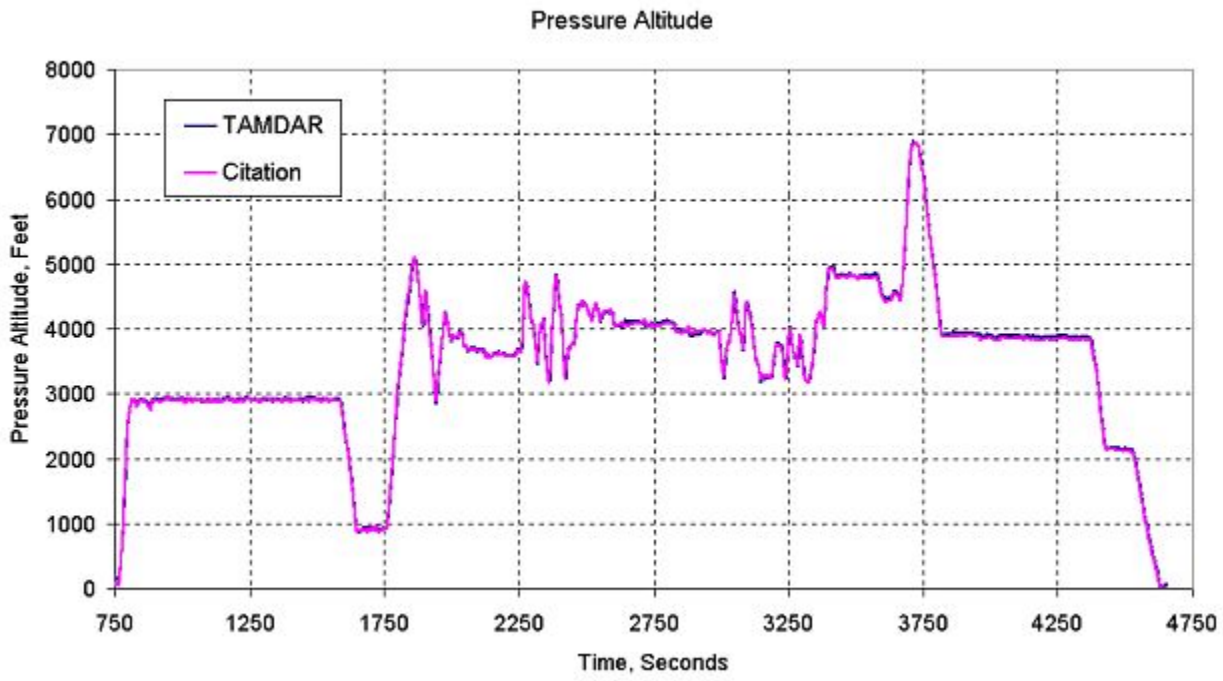

Figure 11. Comparison of pressure altitude from UND Cessna Citation II and TAMDAR sensor

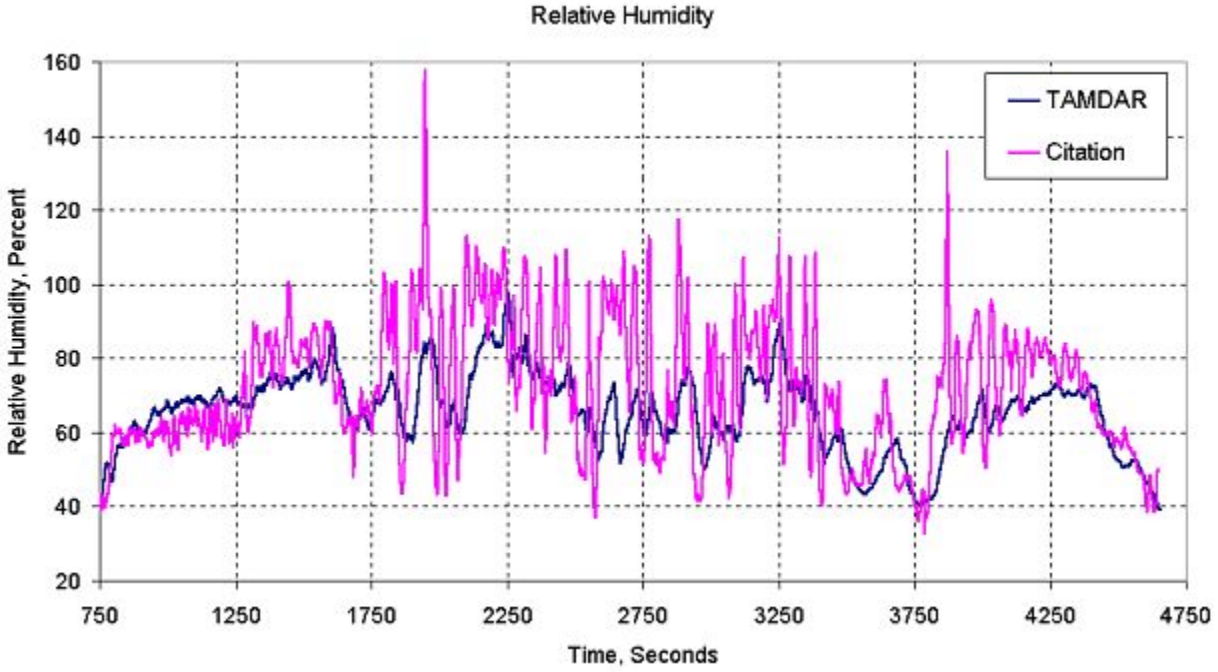

Figure 12. Comparison of relative humidity from UND Cessna Citation II and TAMDAR sensor

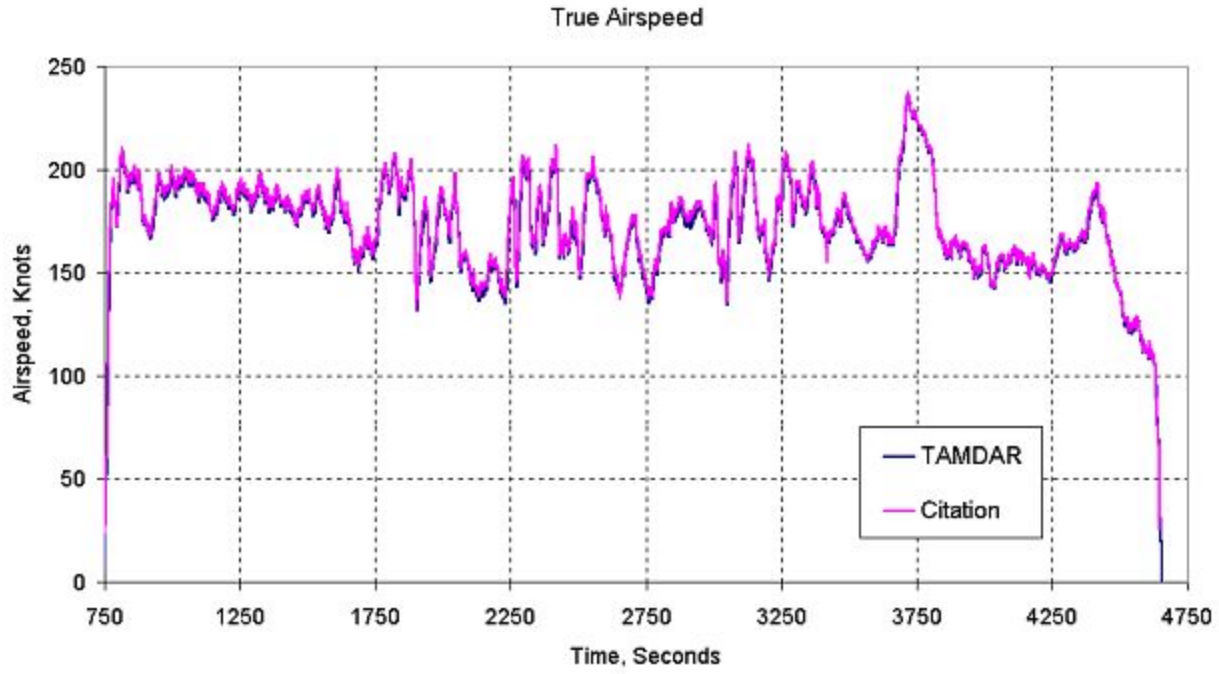

Figure 13. Comparison of true airspeed from UND Cessna Citation II and TAMDAR sensor

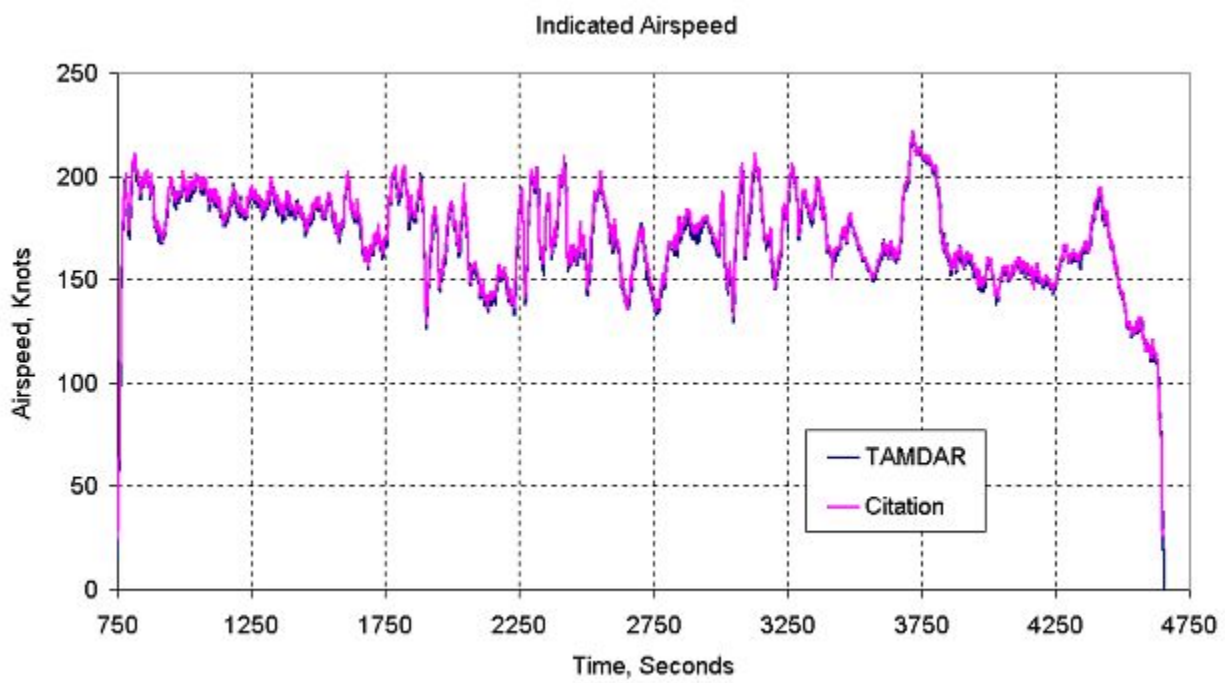

Figure 14. Comparison of indicated airspeed from UND Cessna Citation II and TAMDAR sensor

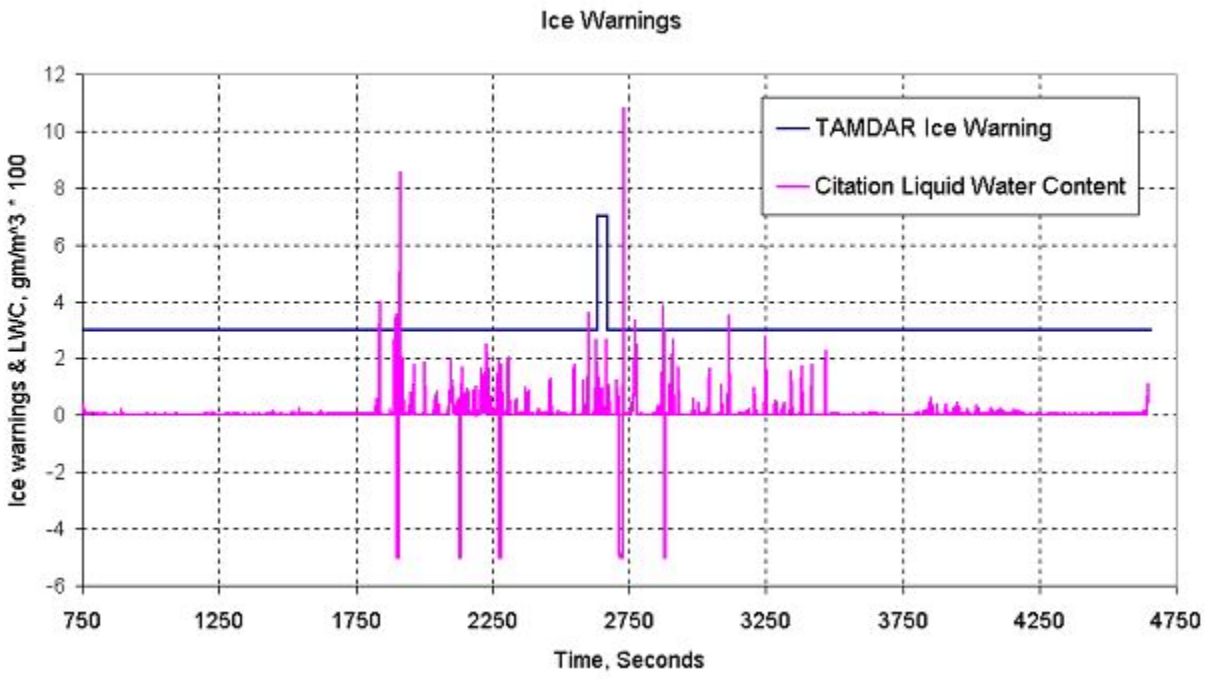

Figure 15. Comparison of icing information from UND Cessna Citation II and TAMDAR sensor

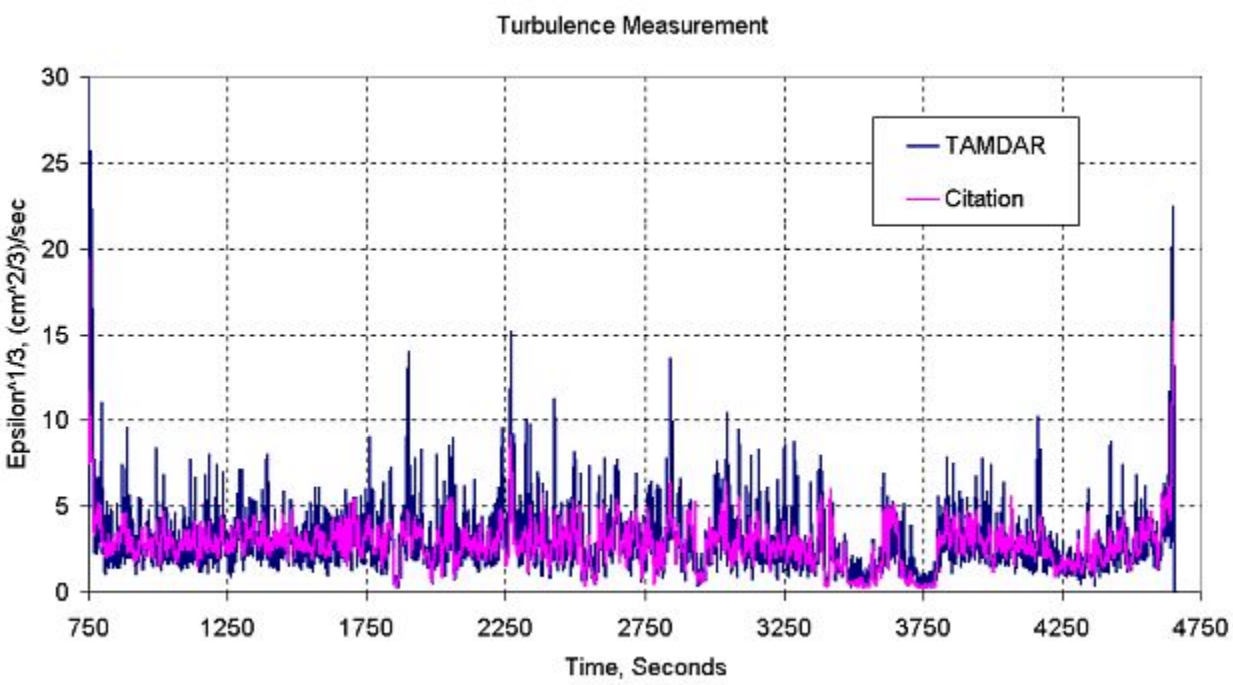

Figure 16. Comparison of eddy dissipation rate from UND Cessna Citation II and TAMDAR sensor

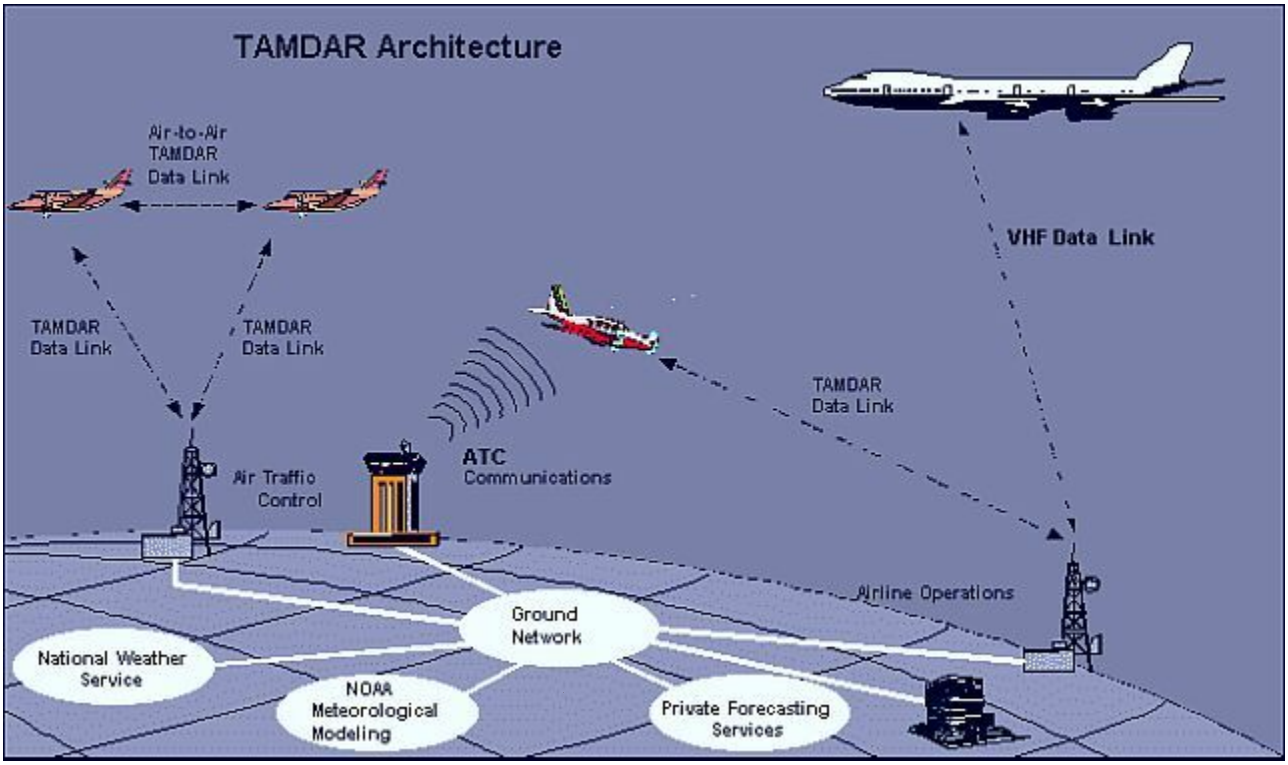

Figure 17. Concept for NAS Implementation of TAMDAR

APPENDIX B

Element	Reporting Range	Reporting Resolution	Measurement Accuracy
I.D.			
A/C Type (Sensor ID)			
Date	Year/Month/Day		
Time	Hour/Minute/Second	Nearest Second	
Latitude	- 90 to 90°/Min.	.001°	
Longitude	-180 to 180°/Min.	.001°	
Pressure Altitude (Geometric Altitude of the Aircraft above Sea Level)	T: 0 to 25,000 Feet O: 0 to 35,000 Feet or higher	T: 300 Feet O: 10 Feet	1070-500 hPa: 30 Feet 500-300 hPa: 45 Feet 300-100 hPa: 60 Feet
Wind Speed	T: 0 to 175 Knots O: 0 to 250 Knots	Nearest Knot	3 Knots
Wind Direction*	0 to 360°	Nearest Degree	5°
Temperature	T: -35 to 50°C O: -90 to 50°C	0.1°	0.5°C
Humidity	0-100 Percent	Nearest 1.0% at all levels	T: 5% O: Less than 5%
Turbulence† (Peak RMS Load)	0 to 0.2 Light 0.2 to 0.3 Moderate 0.3 to 0.6 Severe		
Icing	Yes (Icing Present); or No (No Icing Present)	T: Yes/No & Type O: Accretion Rate	
Data Quality Flag	Yes/No		
Phase of Flight	Ascent/En Route/Descent	Specify Phase	

†Accelerometer-based values for G-loads
*With respect to the ground

Table 1. Data Reporting Requirements

TAMDAR	Sample Rate	Reporting Frequency
Routine Data Collection		
Ascent Report/ Series 1	3-20 sec intervals, default to 6 sec	Collect for 30-200 sec, default to 90 sec
Ascent Report/ Series 2	20-60 sec intervals, default to 20 sec	Collect till top of climb (18-30K), default to 25K
En Route Report	1-60 min intervals, default to 3 min	Collect six consecutive reports, then transmit
Descent Report	20-300 sec intervals, default to 60 sec	Begin at top of descent (18-30K), default to 25K; collect 10 reports, then transmit. Final report on touch down.

Table 2. Reporting Strategy

Parameter	Range	Accuracy	Resolution	Latency
Pressure†	10 -101 Kp	5 millibars	±0.05 millibars	
Temperature	-65 to +65°C	±1°C	±0.1°C	
Humidity	0 to 100%RH	±5% (Below Mach .4) ±10% (Mach .4 - .6)	±1%	6 seconds
Magnetic Heading‡	0-360°	±5°		
Ice Detection		Less than 0.030 inch		

†Accuracy specified for angles of attack less than 10°.
‡For pitch and roll less than 30°

Table 3. Measured Parameters, Aircraft Altitudes 0 to 50,000 feet

Parameter	Range	Accuracy	Resolution
Pressure Altitude	0 – 10,000 ft.	±150 feet†	±10 feet
Pressure Altitude	10,000 – 25,000 ft.	±200 feet†	±10 feet
Pressure Altitude	25,000 – 50,000 ft.	±250 feet†	±10 feet
Indicated Airspeed	70-270 knots	±3 knots†	
True Airspeed	70-450 knots	±4 knots†	
Turbulence(eddy dissipation rate--$\in^{1/3}$)‡	0-20 $cm^{2/3}$ sec^{-1}	N/A	
Winds Aloft*		± 4 knots ±5°	
Ice Accretion Rate	0 to 0.25 inches/minute	N/A	

†Accuracy specified for angles of attack less than 10°.
‡Calculation of eddy dissipation in accordance with McCready Atmospheric Turbulence Scale.
*Winds aloft calculation will require use of GPS and magnetic heading.

Table 4. Derived Parameters, Aircraft Altitudes 0 to 50,000 feet.