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Tropospheric Airborne Meteorological Data Reporting (TAMDAR) Sensor Validation and Verification on National Oceanographic and Atmospheric Administration (NOAA) Lockheed WP-3D Aircraft

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Summary

As part of the National Aeronautics and Space Administration's Aviation Safety and Security Program, the Tropospheric Airborne Meteorological Data Reporting project (TAMDAR) developed a low-cost sensor for aircraft flying in the lower troposphere. This activity was a joint effort with support from Federal Aviation Administration, National Oceanic and Atmospheric Administration, and industry. This paper reports the TAMDAR sensor performance validation and verification, as flown on board NOAA Lockheed WP-3D aircraft. These flight tests were conducted to assess the performance of the TAMDAR sensor for measurements of temperature, relative humidity, and wind parameters.

The ultimate goal was 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 envisioned system will initially be used on regional and package carrier aircraft. The ultimate users of the data are National Centers for Environmental Prediction forecast modelers. Other users include air traffic controllers, flight service stations, and airline weather centers.

NASA worked with an industry partner to develop the sensor. Prototype sensors were subjected to numerous tests in ground and flight facilities. As a result of these earlier tests, many design improvements were made to the sensor. The results of tests on a final version of the sensor are the subject of this report.

The sensor is capable of measuring temperature, relative humidity, pressure, and icing. It can compute pressure altitude, indicated air speed, true air speed, ice presence, wind speed and direction, and eddy dissipation rate. Summary results from the flight test are presented along with corroborative data from aircraft instruments.

Introduction

This paper is a description of flight testing of an aircraft-based weather sensor. The overall development effort was part of the Aviation Safety and Security Program (Ref. 1, 2). After a review of similar weather observation systems, the motivation for the development of this new sensor was provided. Descriptions of the sensor system and the associated ground and flight tests results are included.

Rawinsondes (weather balloon sensors) are sent up twice a day at about 90 locations around the U.S. This weather observing system measures temperature, pressure, wind, and relative humidity at ten second intervals, as the rawinsonde is carried aloft by the balloon. These soundings provide excellent weather measurements from the surface to above 15,240 meters. Rawinsonde data are currently ingested into the weather forecast computer models in particular the Rapid Update Cycle (RUC) model at the NOAA National Centers for Environmental Prediction (NCEP).

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 data collected is the Meteorological Data Collection and Reporting System (MDCRS), where only temperature and wind information are collected during all phases of flight. These data are reported in compliance with the ARINC 620 specification (Ref. 4). Due to the nature of jet transport operations, the majority of data are reported from the major hubs (approximately 60) and from high altitude cruise. During cruise, these aircraft are typically at 9,144 meters or higher, which is well above most weather. Currently, the MDCRS data are also being ingested into the NCEP models. Outside of the United States, a system similar to MDCRS is called Aircraft Meteorological Data Relay (AMDAR).

To improve weather model forecasts, the spatial and temporal sampling of temperature, wind, and relative humidity data are required at greater densities than is currently being collected. There exist large "gaps" in the current weather observation systems. Most of the moisture and convective activity are at altitudes of 7,620 meters 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. A system is required that can collect these three main measurements below 7,620 meters throughout the day and from a spatially distributed dense network. The data must be downlinked in near real time, and then used to improve weather forecasts. 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.

Pilots are the targeted audience for the improved weather information that will result from the TAMDAR data. 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. Other users include air traffic controllers, flight service stations, and airline weather centers.

NASA worked with Georgia Tech Research Institute and AirDat, LLC., of Raleigh, NC to develop the Tropospheric Airborne Meteorological Data Reporting (TAMDAR) sensor. AirDat had developed a few prototype sensors that were subjected to numerous tests in ground and flight facilities. (Ref. 1, 2). As a result of these earlier tests, many design improvements were made to the sensor. The results of the tests on a final version of the sensor are the subject of this report.

To be most effective the development of a new weather observation system needs collaboration between NASA, FAA, NOAA and private industry. NASA took a lead role in this collaboration. A Tri-Agency team was established that developed the concept of operations for this new sensor system.

The flights described herein were part of an ongoing development effort between NASA, Georgia Tech Research Institute and AirDat of an airborne sensor to measure atmospheric parameters. Previous testing of prototypes had been done on the University of North Dakota Citation II, and the Naval Postgraduate School (NPGS) Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS), Twin Otter. The results of the previous tests were used to refine the physical features of the probe and the algorithms incorporated into the firmware of the sensor. This paper presents the data collected from two NOAA WP-3D flights from MacDill Air Force Base in Tampa, Florida.

The first flight provided calibration data for the TAMDAR sensor. The second flight assessed the TAMDAR sensor and validated the sensed data for accuracy in a variety of atmospheric conditions encountered at different altitudes and airspeeds. Atmospheric data from both NOAA

WP-3D's reference instrumentation and an Airborne Vertical Atmospheric Profiling System (AVAPS) dropsonde are compared to the TAMDAR data.

Abbreviations, Symbols, and Acronyms

$\in$	Eddy Dissipation Rate
C1, ···, C9	Validation Test Flight Conditions
AVAPS	Airborne Vertical Atmospheric Profiling System
CFD	Computation Fluid Dynamics
DFT	Discrete Fourier Transform
DIR	Direction
EDR	Eddy Dissipation Rate
FAA	Federal Aviation Administration
FL	Flight Level
FS	Fuselage Station
GPS	Global Positioning System
IAS	Indicated Air Speed
IR	Infrared
IIR	Infinite Impulse Response
IMC	Instrument Meteorological Condition
KSC	Kennedy Space Center
LaRC	Langley Research Center
M^2	Mach number squared
KTS	Knots
MEMS	Micro Electro Mechanical System
Min, Max	Minimum, Maximum
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPGS	Naval Postgraduate School
NWS	National Weather Service
P_D	Dynamic Pressure
P_S	Static Pressure
QA	Quality Assurance
QC	Quality Control
RH	Relative Humidity
RTD	Resistance Temperature Device
RH	Relative Humidity
S1, ···, S4	Sounding Test Flight Conditions
Sec	Seconds
SFM	Seconds from Midnight
SPU	Signal Processing Unit
TAMDAR	Tropospheric Airborne Meteorological Data Reporting
UND	University of North Dakota
V	Velocity
VMC	Visual Meteorological Condition

Sensor Description

The Tri-Agency team determined the specifications shown in Table 1 for the TAMDAR sensor. The NASA team used these specifications to develop the sensor. Table 1 outlines the minimum data elements that need to be included in TAMDAR reports. These requirements are derived from the RTCA DO-252 reporting formats to include the current reporting criteria for MDCRS reports and also modified to reflect the minimum reporting criteria and data input and processing needs of the National Weather Service. A sensor identifier was recommended as a reporting element. Additional elements not listed in Table 1 included average and peak turbulence, but no range, resolution, or accuracy was specified by the Tri-Agency team.

Table 1: Tri-Agency Desired Specifications

Element	Reporting Range	Reporting Resolution	Measurement Accuracy
Date	year/month/day	-	-
Time	hour/minute/second	Nearest second	-
Latitude	- 90 to 90 degrees/minutes	.001 degree	-
Longitude	-180 to 180 degrees/minutes	.001 degree	-
Pressure Altitude	T: 0 to 6100 meter O: 0 to 10700 meter or higher	T: 92 meter O: 3.05	1070-500 kPa: 10 meters 500-300 kPa: 15 meters 300-100 kPa: 20 meters
Wind Speed	T: 0 to 175 knots O: 0 to 250 knots	1 knot	3 knots
Wind Direction	0 to 360 degrees	1 degree	5 degrees
Temperature	T: -35 to 50 degrees C O: -90 to 50 degrees C	0.1 degree	0.5 degrees C
Humidity	0-100 percent	1.0% at all levels	T: 5% O: Less than 5%
Icing	Yes (Icing Present); or No (No Icing Present)	T: Yes/No & Type O: Accretion Rate	-
Data Quality Flag	Yes/No	Roll greater than 5 degrees	-
Phase of Flight	Ascent/En Route/Descent	Specify Phase	-

Where applicable, the requirements are labeled "T" for "Threshold" or "O" for "Objective." Threshold is the minimum performance required for acceptable operational suitability and effectiveness. Objective is the measured increase in capability that has practical operational benefit to the NAS and its users. Threshold values are based primarily on the current performance requirements of the NWS rawinsonde sensor package and are modified when appropriate, to reflect that TAMDAR reports will be originated from aircraft operating primarily below 20,000 feet.

The sensor consists of a probe (external to the aircraft) and an attached signal processing unit. A cutaway view of the probe is shown in Figure 1. In the figure, the leading edge is shown on the left side. The leading edge notch is an ice detection gap. Two pairs of IR transmitter/detectors (shown as upper and lower optical pairs) are mounted side by side. Ice detection occurs when both IR beams are blocked and the sensed temperature is less than 10ºC. If ice is detected, then the leading and trailing edge heaters are powered to melt the accumulated ice.

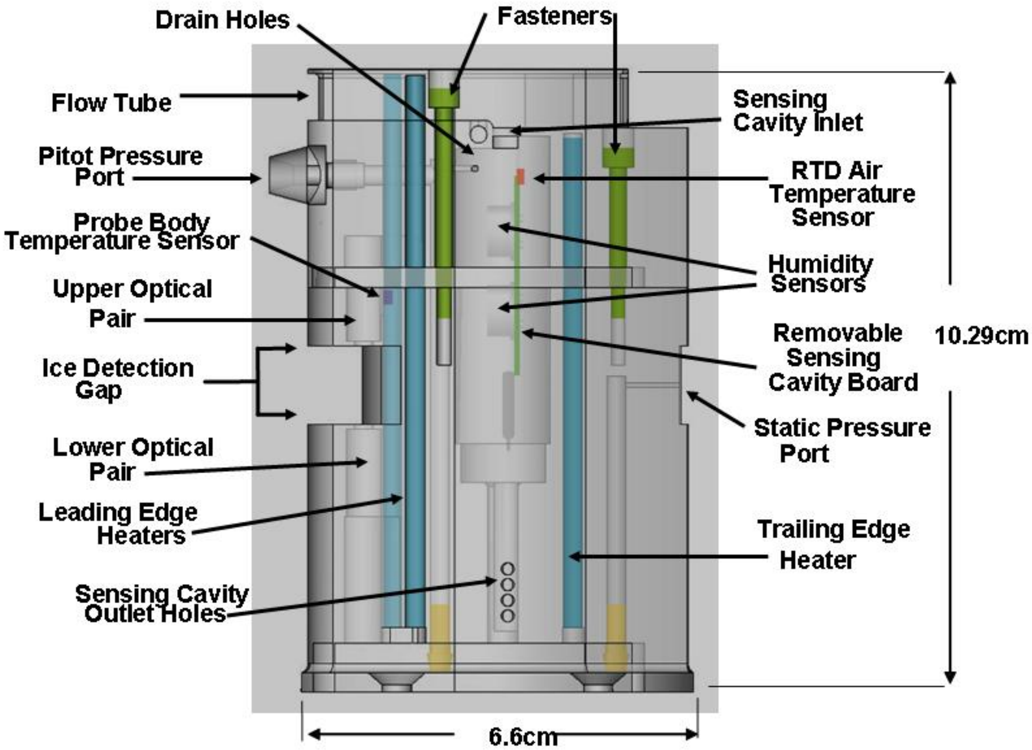

Figure 1. TAMDAR Probe Detail.

The pitot pressure port is located on the leading edge. The associated static pressure port is located on the trailing edge. A differential pressure transducer located in the signal processing unit is connected to these two ports. The SPU and sensor probe are shown in Figure 2.

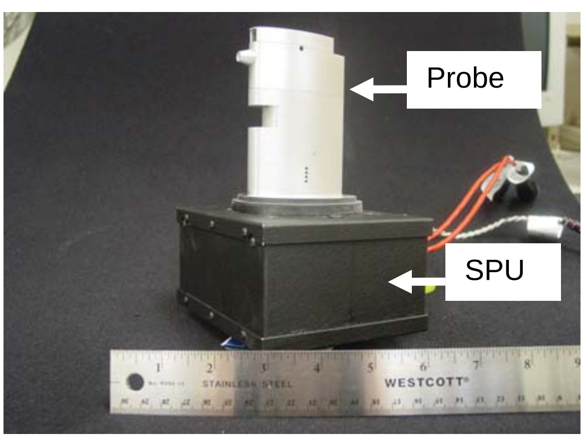

Figure 2. TAMDAR Sensor.

A flow tube at the tip of the sensor has an internal shape that allows airflow to be directed into a sensing cavity. Within this cavity, a removable printed circuit board is installed. This board is equipped with an RTD air temperature sensor and two relative humidity sensors. The RH sensors were Hycal 3610-002 supplied with factory calibration data. Near the base of the sensor are 8 (four per side) outlet holes allowing continuous discharge airflow through the sensing cavity.

Additional physical sensor specifications are listed in Table 2. The basic parameters (range, accuracy, resolution, and latency) measured by the sensor are listed in Table 3. From these measurements, derived parameters are calculated, as listed in Table 4.

Table 2: General specifications

Patented Ice Optical Sensing Technology	Microprocessor based pulse modulation, utilizing high power LED's emitting in the infrared range
Operating Limits	-70C to +65C, Altitude 15,240 m, Humidity 0-100%
Probe Mechanical Specifications	Airfoil Type: 9.82cm height, 6.40cm chord, 1.91cm thickness, 0.812" pitot extension, 0.477cm base flange thickness. 6061 T6 anodized aluminum. Drag: 2.22 N at 220 knots
Electronics Module (SPU) Mechanical Specifications	W13.08cm X L10.49cm X H7.87cm (not including connectors)
Power Requirements	12 to 35 VDC (>26VDC nominal for proper deicing), 6 Watts average electrical load de-icing heaters not engaged; 300 Watts electrical load de-icing heaters engaged @ 28VDC input.
Measurement Sampling Rate	10.7 Hz for sensors, 0.333 Hz for turbulence. Data (except that used for the turbulence calculation) is filtered with a 10 sec response IIR digital filter.
Serial Ports	3 RS-232
Weight	Probe and electronics module approx. 0.77 kg
Design Life	Probe: 20,000 hours. Electronics Module: 50,000 hour MTBF

Table 3: Measured parameters

Parameter	Range	Accuracy	Resolution	Latency (See Note 1)	Comments
Pressure	10 -101 kPa	3 hPa	0.05 hPa	10 sec	See Note2.
Temperature	-70 to +65°C	± 1°C	0.1°C	10 sec	
Humidity	0 to 100%RH	± 5% (typical) ± 10% (typical)	1% (RH > 10%) 0.1% (RH < 10%)	10 sec	Below Mach 0.4 Mach 0.4 - 0.6 (RH from 2 separate sensors is reported)
Heading	0-360°	± 3°	0.1°	10 sec	@ < 30° pitch & roll
Ice Detection		0.508 mm			

Table 4: Derived parameters

Parameter	Range	Accuracy	Resolution	Latency	Notes
Pressure Altitude	0 – 7,620 m	± 45.7 m	3.05 m	10 sec	2
Pressure Altitude	7,620 m – 15,240 m	± 76.2 m	3.05 m	10 sec	2
Indicated Airspeed	70-270 knots	± 3 knots	1 knot	10 sec	2
True Airspeed	70-450 knots	± 4knots	1 knot	10 sec	2
Turbulence (eddy dissipation rate--$\epsilon^{1/3}$); Peak and Median	0-1 $m^{2/3} sec^{-1}$	-	-	3 sec	3
Winds Aloft	-	± 6 knots vector magnitude error	1 knot, 1 deg	10 sec	4

Notes for Tables 3 and 4:

1. 10-second latency is caused by digital filtering of the data, as recommended in the AMDAR Reference Manual, 2003.
2. Accuracy specified for angles of attack less than +/-8° from nominal except for winds aloft whose accuracy depends on the heading sensor used.
3. Turbulence determination: calculation of eddy dissipation rate is in accordance with MacCready (Ref. 3), horizontal EDR calculated from 32 point DFT of TAS (3 sec block).
4. Winds aloft calculation will require use of GPS and magnetic heading. Accuracy depends on relative magnitude and direction of vectors.

The signal processing unit contains a processor capable of performing the floating-point math calculations necessary to compute the derived parameters from basic measurements. These data are then formatted, and output from a serial port to either a PC or a satellite transceiver. A built-in Global Positioning System unit provides time, latitude and longitude stamping for each observation. It also provides the ground track, which is needed for the winds aloft calculation. Externally provided heading is also used in the winds aloft calculation.

Firmware containing the algorithms used to process the measured and the derived parameters resides on programmable read only memory within the signal processing unit. This memory chip is electrically re-programmable, thus, new algorithms, sampling rates, or calibration constants can be updated.

The ARINC 620 specification (time-based reporting) was used in a modified form to report the additional data (icing and turbulence). Also, the specification was modified to include provision for pressure-based reporting as specified in Table 5. Departure field pressure is automatically determined at the moment, when TAS exceeds 80 knots. Special observations are triggered by an icing onset and the firmware defaults are adjustable by remote command via the datalink.

Table 5: Pressure and Time Reporting Schedule

Pressure Observation Interval	Ambient Pressure
10 hPa	greater than departure field pressure minus 200 hPa
20 hPa	less than departure field pressure minus 200 hPa
Time Default	Observation Interval
3 Minutes	greater than 465 hPa (<6,100 m)
7 Minutes	less than 465 hPa (>6,100 m)

Based on the design considerations described above, different versions of the TAMDAR sensor were fabricated. With each version, various tests were conducted to evaluate the changes to the design. The TAMDAR sensor design has undergone numerous improvements. Of particular note are the various wind tunnel tests to improve the flow qualities. In addition, computational fluid dynamics studies were conducted to determine suitable locations for the static pressure port. An internal air sampling chamber was designed to have continuous air flow, even while subjected to large pitch, yaw, and roll angle excursions. Within the internal air sampling chamber, there are two separate RH sensors. These sensors have been tested and calibrated in environmental chambers.

In addition, prior to all the flight tests, the TAMDAR sensor was subjected to the following ground-based tests: vibration, thermal, pressure, and voltage spike as specified in RTCA DO-160D (Ref. 4). The successful results from all of these tests enabled the subsequent flight testing phase.

CFD Analyses

Prior to flight testing on the NOAA WP-3D aircraft, several computational fluid dynamics (CFD) simulations were performed on the TAMDAR sensor. These were performed to show the TAMDAR sensor geometry effects on aerodynamic flow at various attitudes and airspeeds. These types of characterizations were conducted to preclude design deficiencies that might have been revealed in subsequent wind tunnel and flight tests.

Sensor Flight Testing

In addition to the ground tests, numerous flight tests were conducted on various aircraft to support the refinement of the TAMDAR sensor design and to validate performance against standard instruments. Three flights were conducted on one of NOAA's WP-3D "Hurricane Hunters", shown in Figure 3. The Department of Commerce owns and operates WP-3D aircraft for the purpose of atmospheric research by NOAA. The WP-3D is a four engine turboprop plane capable of long duration flights (8-12 hours). As shown in the Appendix, a variety of meteorological research and data acquisition instrumentation is available. Because this aircraft is instrumented for performing atmospheric research, it was selected to measure data for comparison (Ref. 3). Three flights were conducted on one NOAA's WP-3D "Hurricane Hunters", shown in figure 3. The aircraft was flown to a region west of Tampa over the Gulf of Mexico. The first flight was conducted to perform airflow analysis at the TAMDAR installation site on the WP-3D. The second flight was conducted to calibrate the TAMDAR sensor and third flight was to assess the TAMDAR sensor and validate the measured data for accuracy. Each of the three flights was performed at the same sets of altitudes and airspeeds. Atmospheric data from both NOAA WP-3D's reference instrumentation and an Airborne Vertical Atmospheric Profiling System (AVAPS) dropsonde are compared to the TAMDAR data.

Figure 3. NOAA WP-3D.

Sensor Configuration

As shown in Figure 4, the pedestal was used for mounting the TAMDAR probe onto the window plate. This resulted in separating the probe from the SPU. Connectors were added to the side of the SPU and extension cables connected the probe electronics to the SPU connectors. Pressure tubing connected the static and pitot ports to barbs on the SPU unit. This configuration insured that the probe was outside the boundary layer of the aircraft fuselage. Normally the flange on the sensor probe base is flush with the aircraft skin. With the pedestal, the sensor probe base is about 10 centimeters above the aircraft skin.

The standard TAMDAR internal GPS (Garmin TM GPS-15L) connected to an antenna on top of the fuselage was used. Normally, the TAMDAR system uses an Iridium TM satellite datalink and hence a satellite antenna is required. No satellite antenna was available on the WP-3D, so TAMDAR data were recorded on-board the plane for later retrieval.

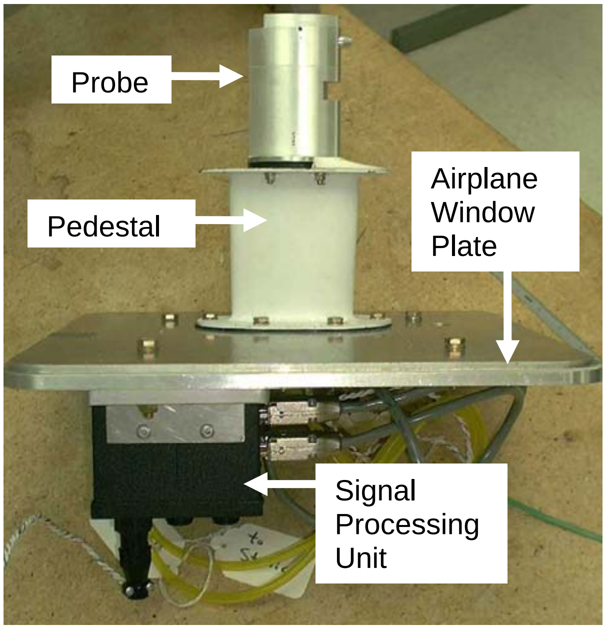

Figure 4. TAMDAR Probe, Pedestal, and SPU on Mounting Plate.

Installation

Normally, the probe is oriented downward to facilitate drainage. But in this case, the TAMDAR probe on the pedestal was mounted on the side of the aircraft at approximately 30 degrees above horizontal. An important consideration in selecting the final location was the minimization of turbulent airflow that could adversely affect turbulence, airspeed, and pressure altitude measurements. Figure 5 is a schematic of two views of a Lockheed Orion P-3, similar to the WP-3D, showing the location of the installed TAMDAR sensor.

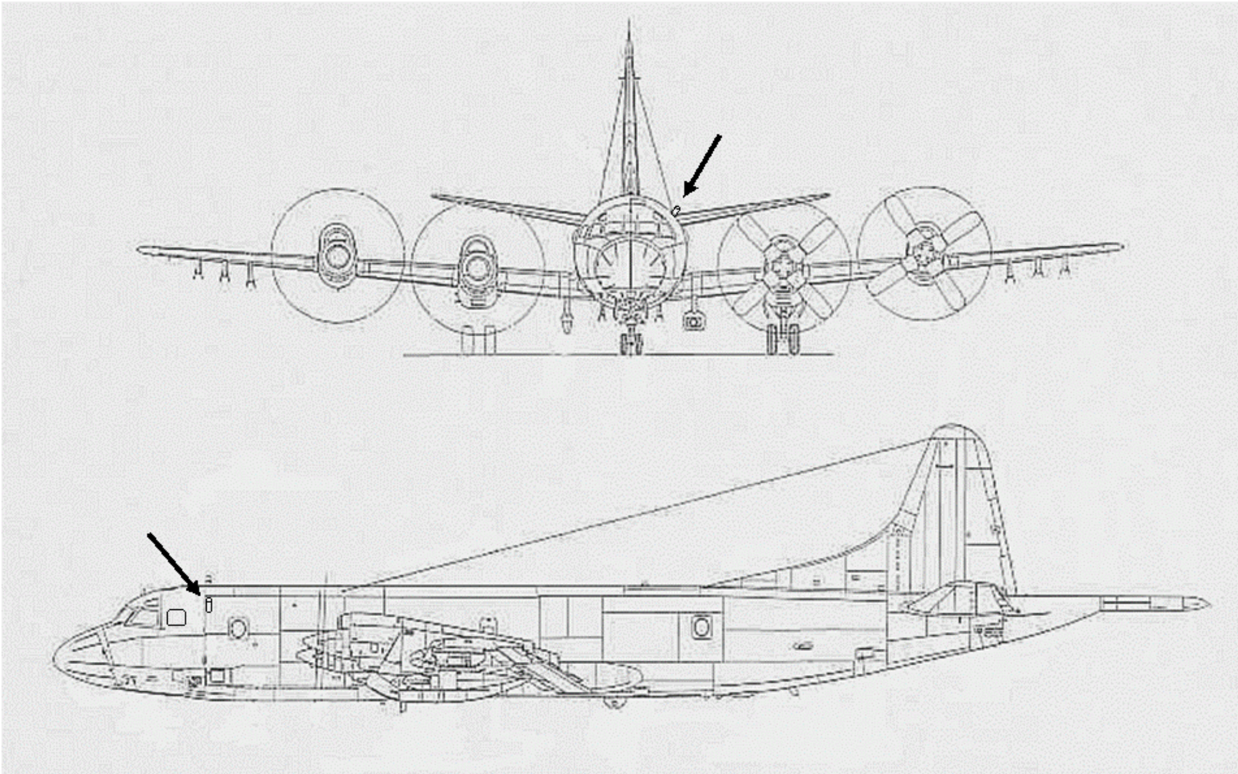

Figure 5. Schematic Views of the Orion P-3

On the WP-3D, the boundary layer from the skin is roughly 2.5 centimeter away for every 2.5 meters distance from the nose of the aircraft (Ref. 5). As shown in Figure 6, the TAMDAR sensor was installed on a 10 centimeter pedestal at fuselage station (FS) 312, which is 3.96 meters from the nose. At this location, the boundary layer is approximately 4 centimeters in depth. Thus, the TAMDAR sensor was installed outside the boundary layer. Figure 7 is a close-up view of the installation.

Figure 6. WP-3D with TAMDAR Installed.

Figure 7. Close-up View of TAMDAR Installed.

In Figure 8, a block diagram of the TAMDAR interface to the WP-3D data computer is shown. Aircraft heading was supplied to the TAMDAR sensor by the WP-3D inertial navigation system (Litton TM Model LTN-72) via ARINC 575 and RS-232 busses. WP-3D aircraft reference instrument data was logged onto an on-board computer, while a separate laptop computer logged the TAMDAR data. In addition to the TAMDAR data being logged on the laptop, TAMDAR and WP-3D reference data was hand-recorded during the flights. The SPU and other instrumentation are shown in Figure 9.

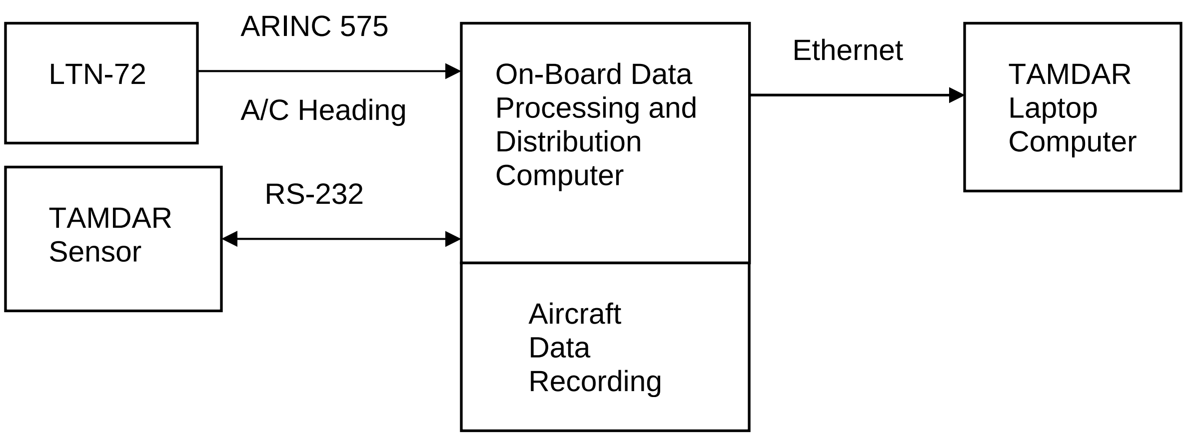

Figure 8. WP-3D TAMDAR Interface Block Diagram.

Figure 9. TAMDAR SPU Installation.

Airflow Analysis

Prior to the calibration flight, an airflow analysis was performed. This characterization was done by installing a pitot/static probe in place of the TAMDAR probe. This flight test consisted of a series of runs at three altitudes and airspeeds. The altitudes were 6100, 3200, and 450 meters, while the airspeeds (IAS) were 230 knots, 210 knots, and 180 knots, leading to a total of nine different altitude/airspeed combinations.

A pitot static pressure probe could be extended and retracted manually in flight. Thus, while in flight, the pressure probe distance from the mounting plate could be varied. Data from the pitot/static probe were recorded, while the probe was adjusted to three different distances of 18.4, 16.3, and 10 centimeters from the aircraft skin. All data used in the analysis were selected from level flight in either a headwind or tailwind condition, alleviating aircraft fuselage flow disturbance. The dimensional distances of the TAMDAR probe, pitot and static pressure ports, and the probe base flange from the mounting plate are shown in Figure 10.

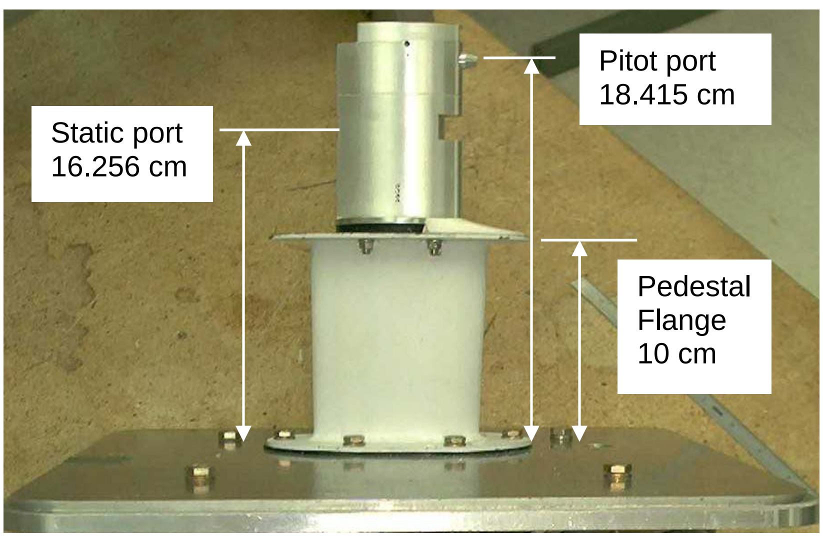

Figure 10. Pedestal and Probe Dimensions.

The pitot static probe was held at distances of 18.4, 16.3, and 10 centimeters (from the mounting plate installed at the fuselage mold line) for at least 60 seconds, resulting in twenty-seven different sets of static and dynamic pressure data.

All of these cases were analyzed and found to show similar results. The static pressure measurements were taken concurrently with the dynamic pressure measurements under the same conditions.

Post flight data analysis indicated lack of significant fluctuations on the test flight data and indicative of fairly undisturbed airflow at FS 312 beyond 10 centimeters, therefore, that position was deemed to be a suitable location for the TAMDAR probe installation.

Calibration Flight

Since a TAMDAR sensor had not previously been flown on a WP-3D, a calibration flight was performed to enable post flight adjustment of various calibration constants. The calibration constants from a previous flight on a different aircraft were initially programmed into the WP-3D TAMDAR SPU as a starting point. Post analysis of the data resulted in new set of calibration constants. The constants requiring adjustment were the mach heating constant (π), and the airspeed correction for pressure altitude constants (K_{DYN1} and K_{DYN2}). The final values for these constants were K_{DYN1}=0.0141, K_{DYN2}=-1.699, and $\pi = 0.17$. These calibration values were held constant throughout the rest of the test flights. The calibration constants were updated to correct the altitude dependence of the airspeed measurement. The firmware was upgraded to include the new calibration values before the validation flights.

Validation Flight

The third flight was conducted after the new calibration constants were uploaded to the SPU via the serial port. This flight consisted of a leg from MacDill AFB to an area above the Gulf of Mexico (with several racetrack patterns at various altitudes), and a return leg to MacDill AFB. As with the airflow and calibration flights, the same set of nine combinations of airspeed and altitude were performed. The total flight was segmented into nine separate events based upon airspeed and altitude. The ground tracks for each of the flight segments were similar. A sample flight track is shown in Figure 11. Negative values for Longitude indicate "west" of the Prime Meridian. For the long legs of each segment, the aircraft was aligned with the tailwind or the headwind. The exception occurred at two of the low altitude segments, where crosswind data was desired. The elongated loops were converted into square flight patterns. A sample of this pattern is shown in Figure 12.

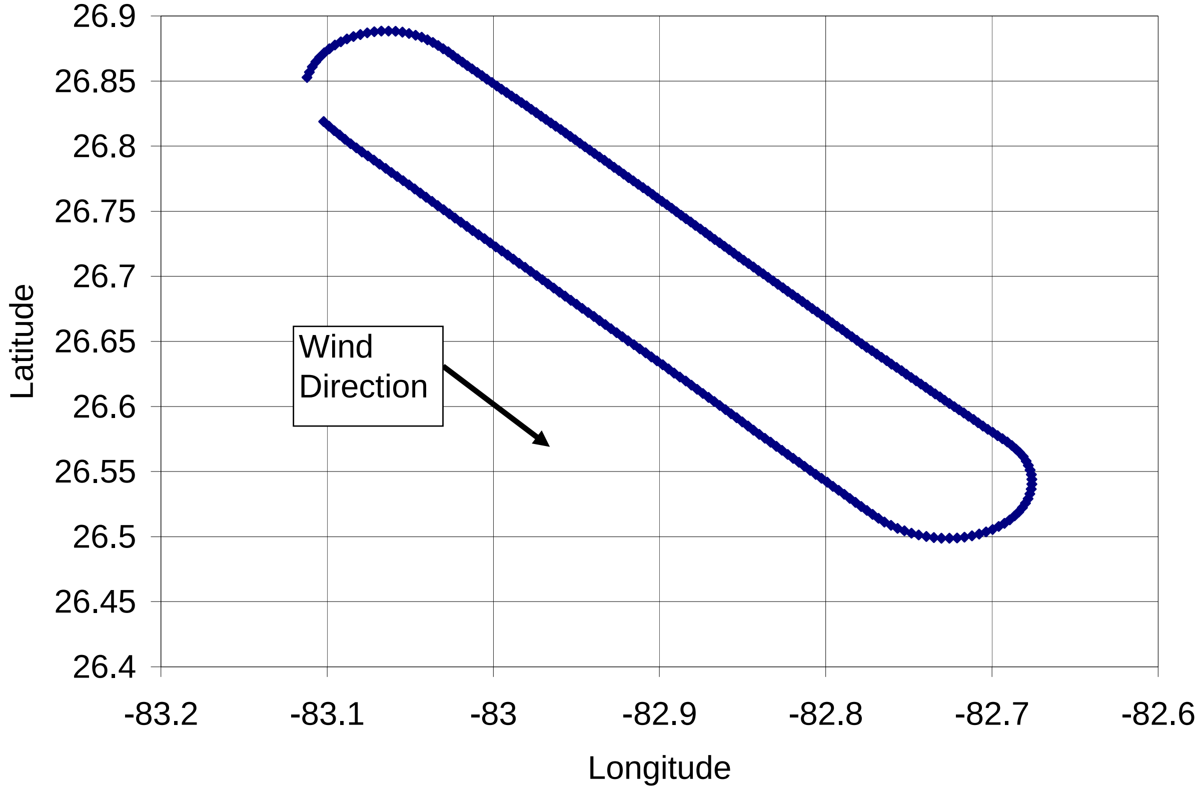

Figure 11. Flight Test Pattern at 6,100 m Altitude and 210 knots TAS

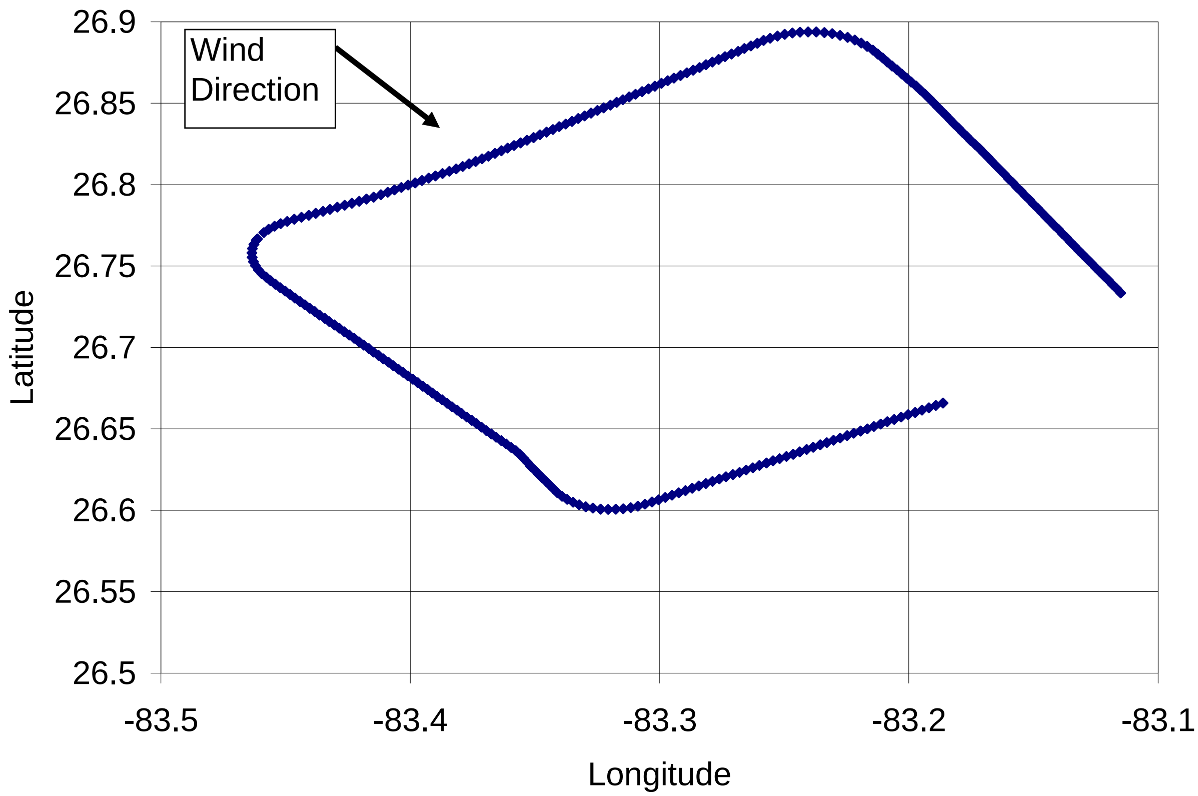

Figure 12. Flight Test Pattern at 460 m Altitude and 210 knots TAS

Sensor Validation Flight Results

The nine airspeed and altitude combinations are listed in Table 6. For convenience, each combination or flight segment is labeled “C1”, “C2”, etc. These labels are used in subsequent tables of data analysis to refer to these specific flight conditions. Other flight conditions that constrained all data acquired includes straight level flight without any turns. Only obviously errant data points were eliminated for the error analysis. The flight data was analyzed by comparing the temporal TAMDAR data with the WP-3D reference data.

Table 6. Airspeed and Altitude Combinations

Flight Segment	C1	C2	C3	C4	C5	C6	C7	C8	C9
IAS (kts)	215	235	185	180	205	230	185	195	220
Altitude (m)	6,100	6,100	6,100	3,050	3,050	3,050	460	460	460
Number of Obs	274	241	332	280	263	236	263	279	300

Analysis was performed for each flight segment by comparing each TAMDAR parameter (with the exception of turbulence and icing) with the corresponding WP-3D values. The TAMDAR data are recorded at 0.33 Hz while the WP-3D data system records data at 1 Hz. This sampling rate difference resulted in the need to preprocess the WP-3D data by sub-sampling. This was not a decimation process, as no filtering was performed on the WP-3D data. The comparison data was time synchronized prior to differencing to yield error values. The mean and standard deviation of each error set for each flight segment was then computed. For example, the flight segment “C1” had 274 data points for comparison. This data set was recorded while the WP-3D was flying at airspeed of 215 knots and at an altitude of 6,100 meters.

The results of temperature data analysis for each of the nine flight segments are listed in Table 7. Continuing the previous example, analysis of temperature data for flight segment “C1” yields a mean error of 0.315 ºC, a standard deviation of 0.202 ºC, a minimum error of -0.417 ºC, and a maximum error of 0.931 ºC.

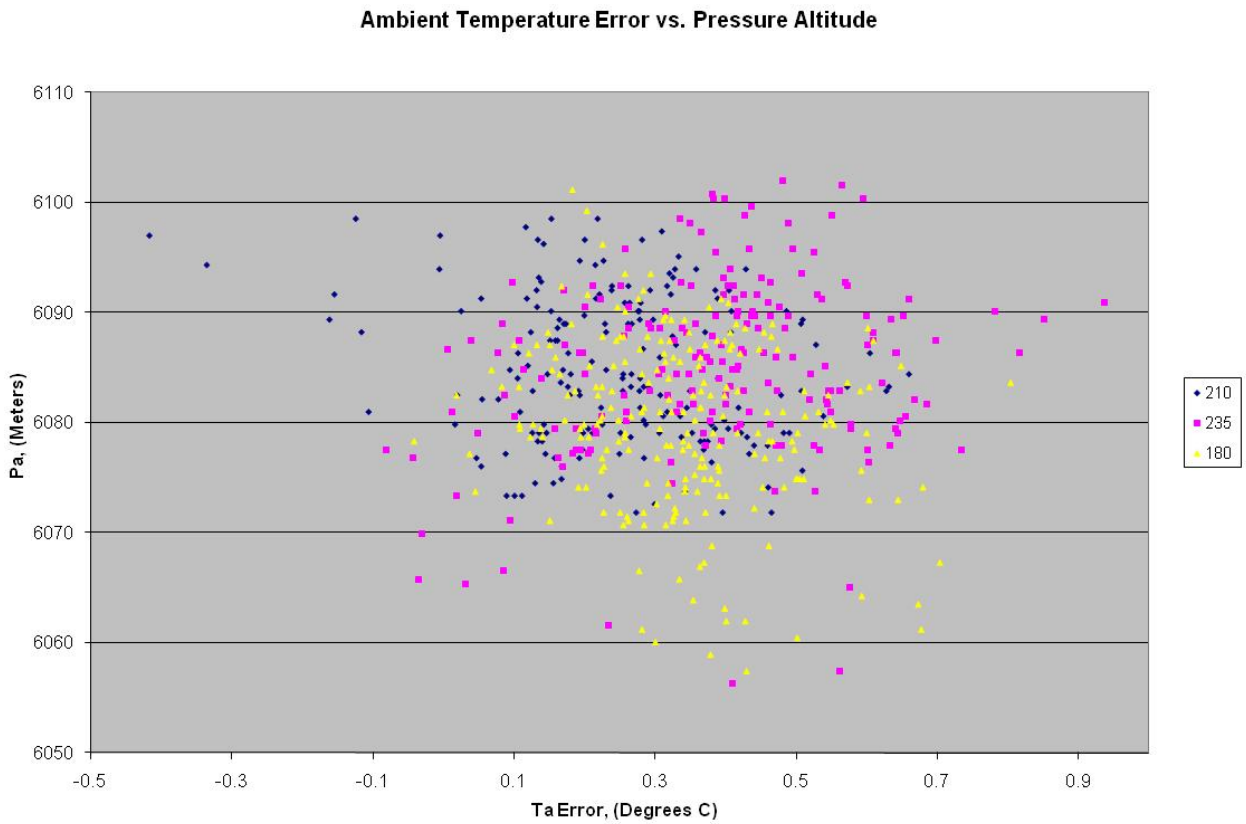

Figure 13 Ambient Temperature Error vs pressure Attitude at 6080 +/-30 meters

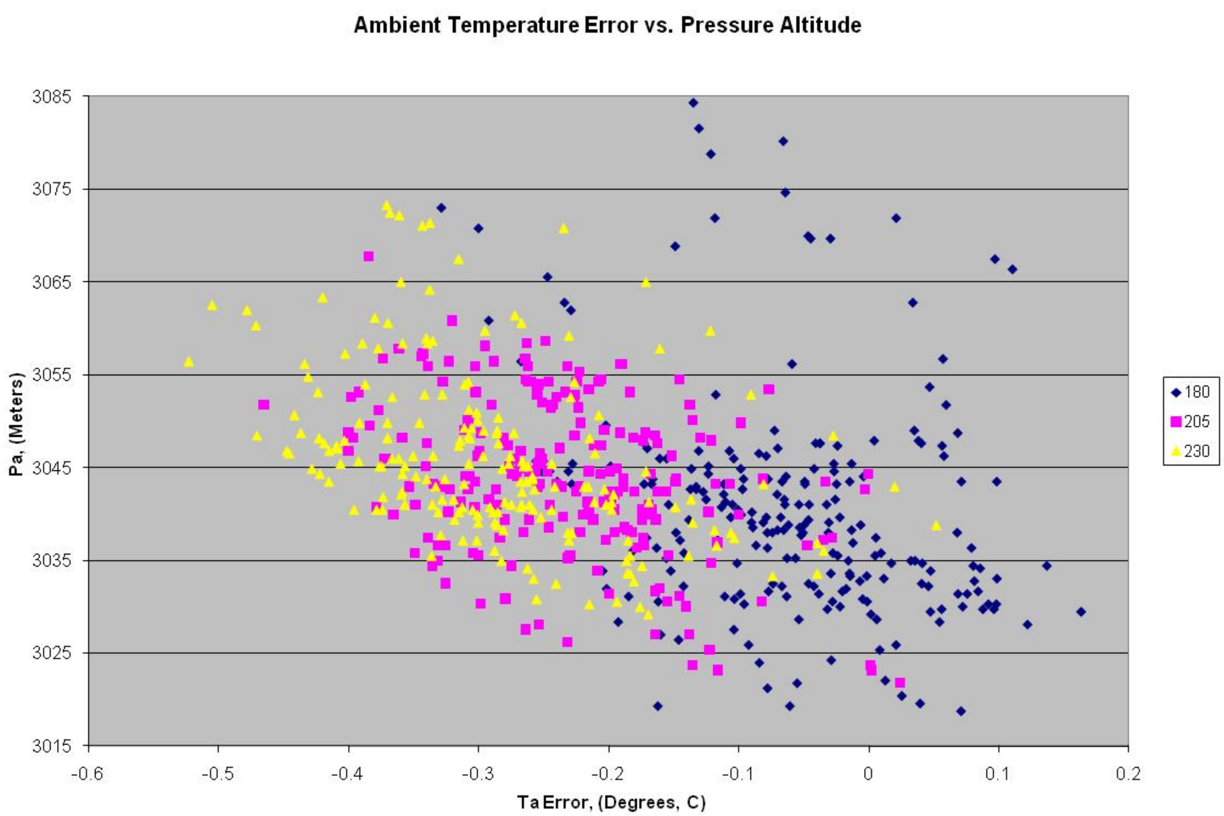

Figure 14 Ambient Temperature Error vs pressure Attitude at 3050 +/-35 meters

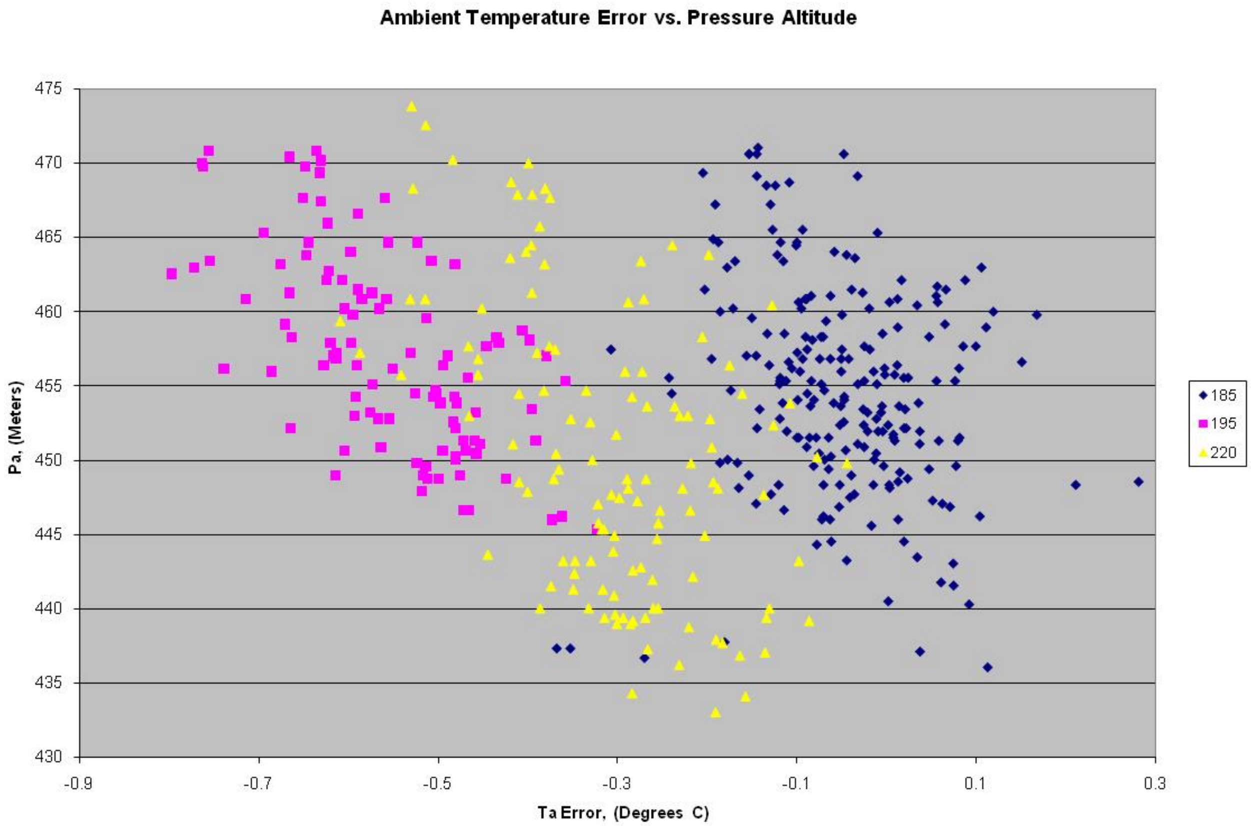

Figure 15 Ambient Temperature Error vs pressure Attitude at 452 +/-22 meters

Table 7. Temperature Validation Results

Temperature (ºC)									
Flight Segment	C1	C2	C3	C4	C5	C6	C7	C8	C9
Mean Error	0.315	0.470	0.341	-0.031	-0.211	-0.275	-0.054	-0.540	-0.304
Stan. Dev. Error	0.202	0.275	0.169	0.118	0.102	0.109	0.123	0.098	0.122
Minimum	-0.417	-0.082	-0.393	-0.329	-0.465	-0.523	-0.653	-0.797	-0.617
Maximum	0.931	1.557	0.804	0.428	0.115	0.055	0.292	-0.180	0.028

The results of relative humidity data analysis for each of the nine flight segments are listed in Table 8. Continuing the previous example, analysis of relative humidity data for flight segment "C1" yields a mean error of -4.3%, a standard deviation of 0.6%, a minimum error of -5.8%, and a maximum error of -3%.

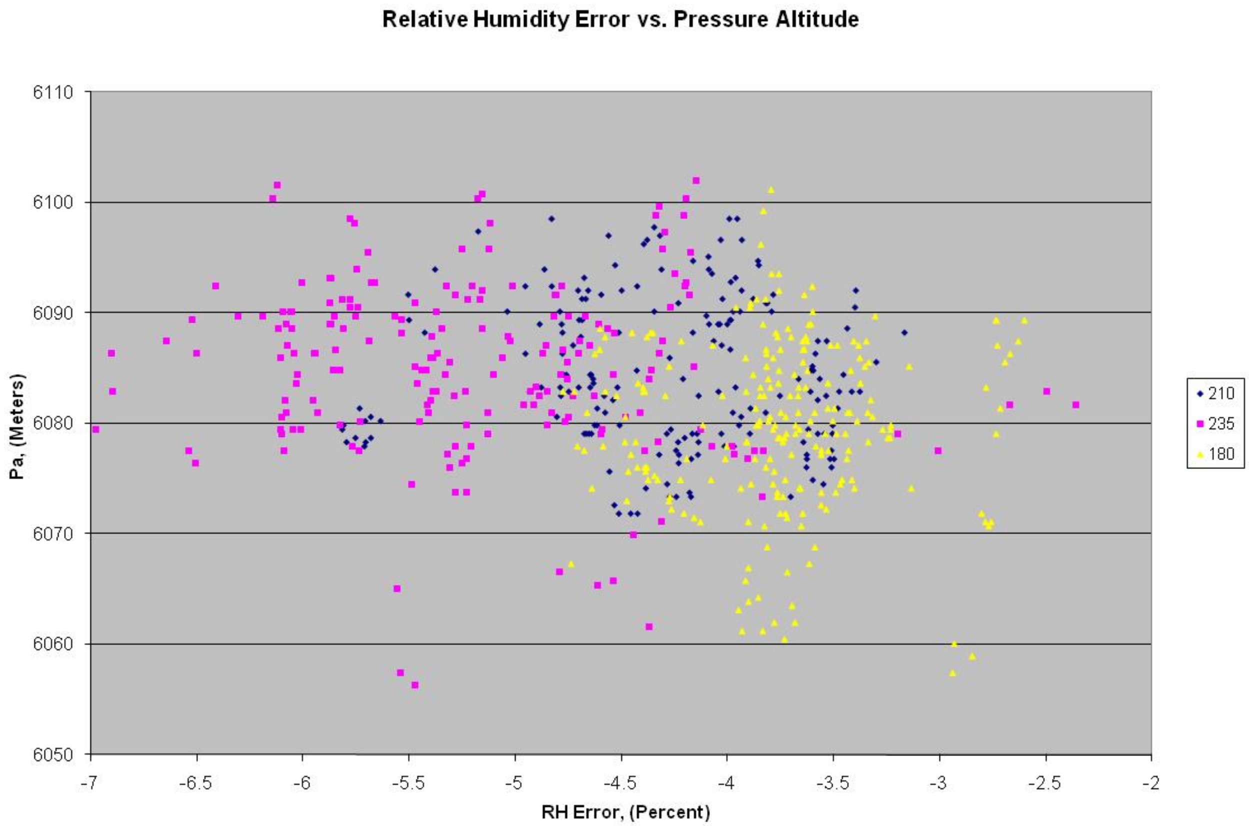

Figure 16 Relative Humidity vs Pressure Altitude at 6080 +/- 30 meters

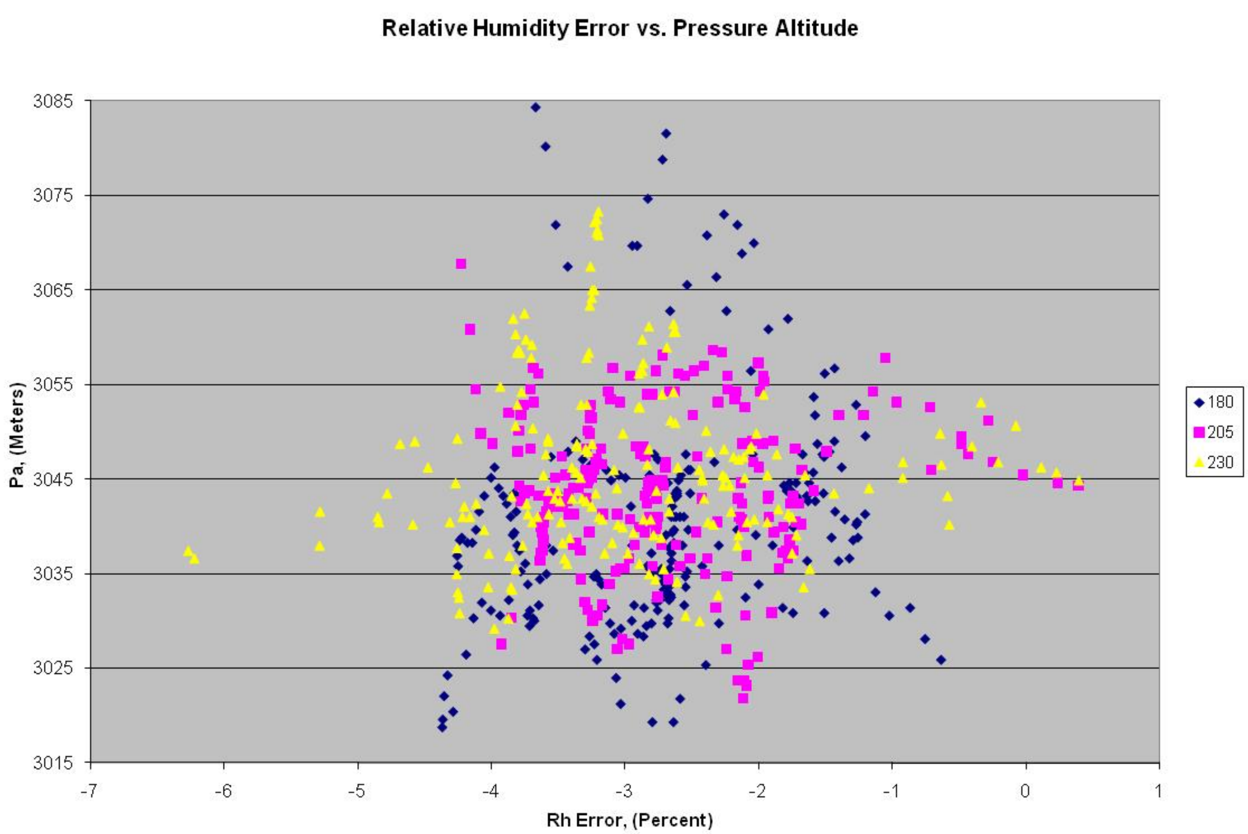

Figure 17 Relative Humidity vs Pressure Altitude at 3050 +/- 35 meters

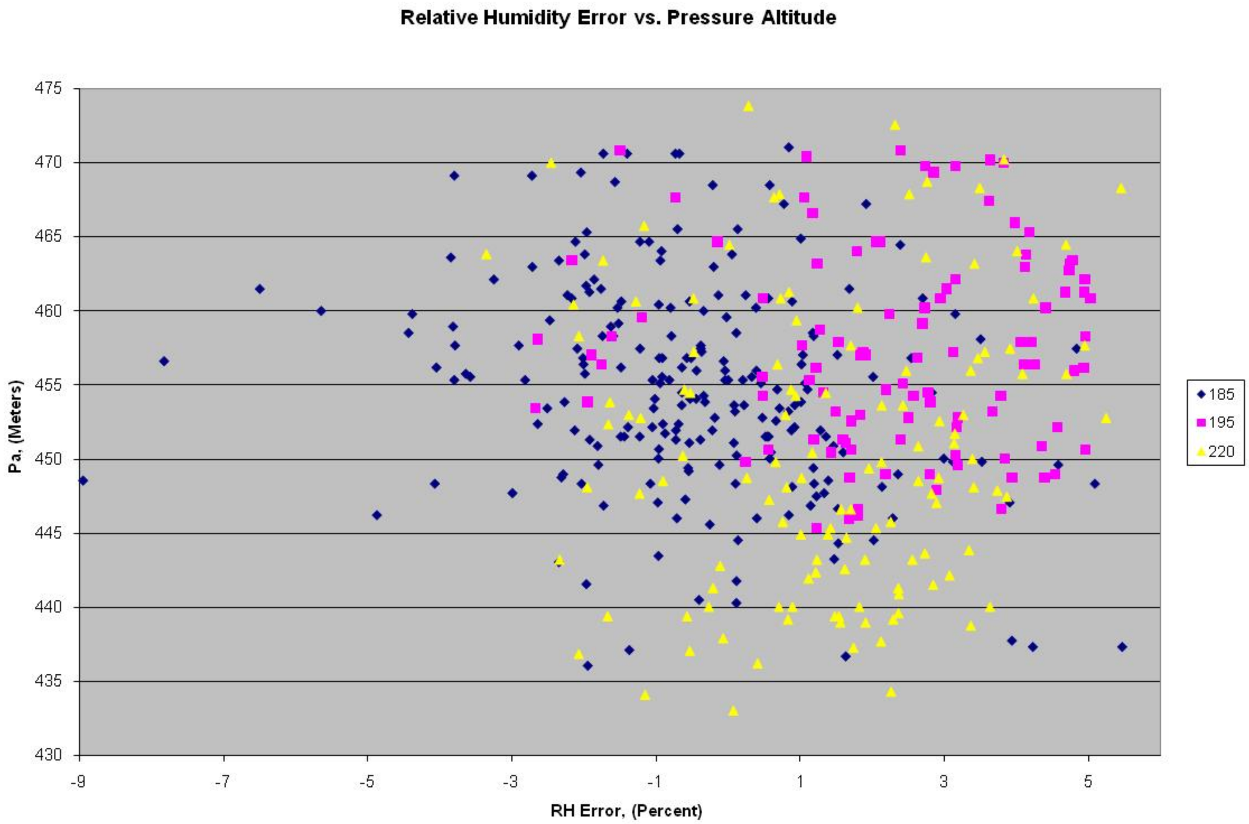

Figure 18 Relative Humidity vs Pressure Altitude at 452 +/- 22 meters

Table 8. Relative Humidity Validation Results

Relative Humidity (percent)									
Flight Segment	C1	C2	C3	C4	C5	C6	C7	C8	C9
Mean Error	-4.318	-5.023	-3.609	-2.991	-2.966	-3.231	-0.506	2.314	1.491
Stan. Dev. Error	0.5859	0.947	0.727	1.137	1.117	1.188	2.801	1.874	2.122
Minimum	-5.815	-6.977	-4.845	-6.391	-6.455	-6.451	-11.36	-3.833	-7.241
Maximum	-3.026	-1.790	-0.971	-0.635	0.392	0.398	12.78	6.194	6.497

The results of the indicated airspeed data analysis for each of the nine flight segments are listed in Table 9. Continuing the previous example, analysis of indicated airspeed data for flight segment "C1" yields a mean error of -2.1 knots, a standard deviation of 2.8 knots, a minimum error of -11 knots, and a maximum error of 7.2 knots.

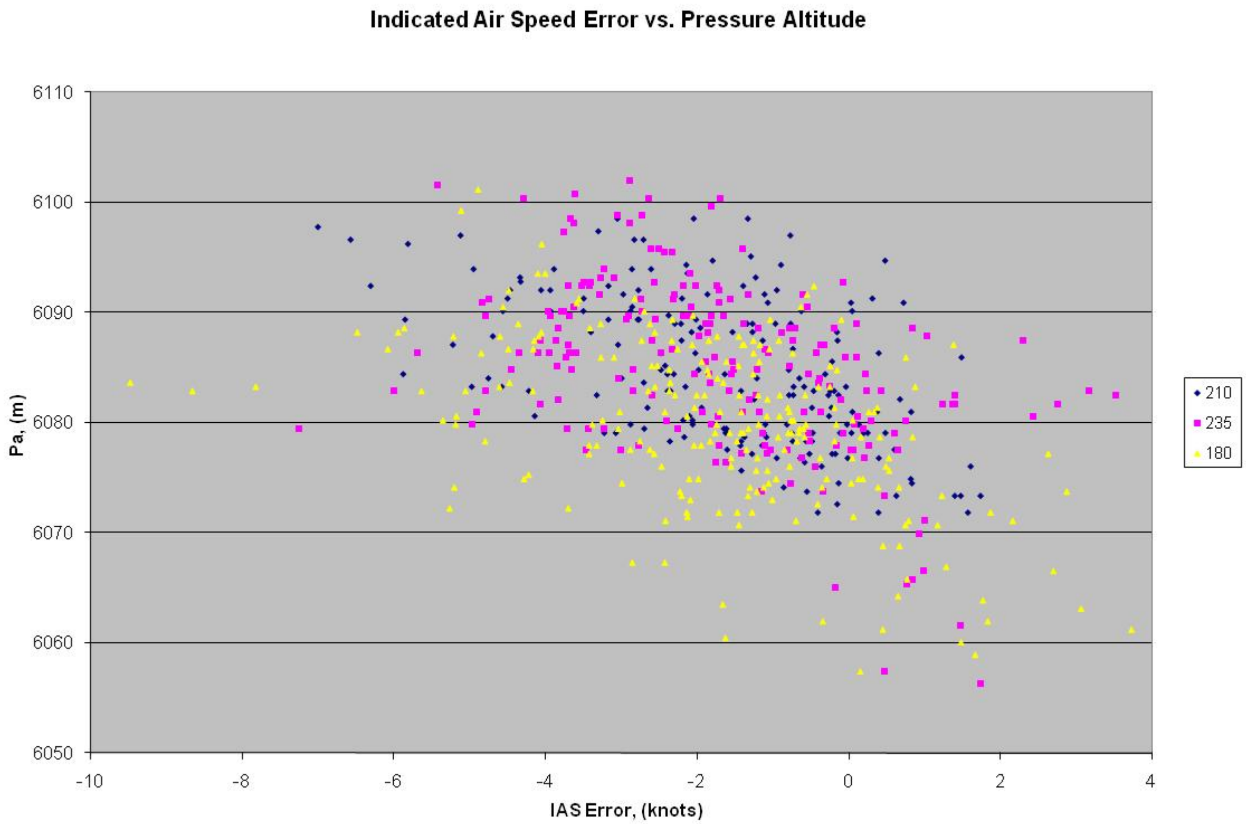

Figure 19 Indicated Air Speed Error vs Pressure Altitude at 6080 +/- 30 meters

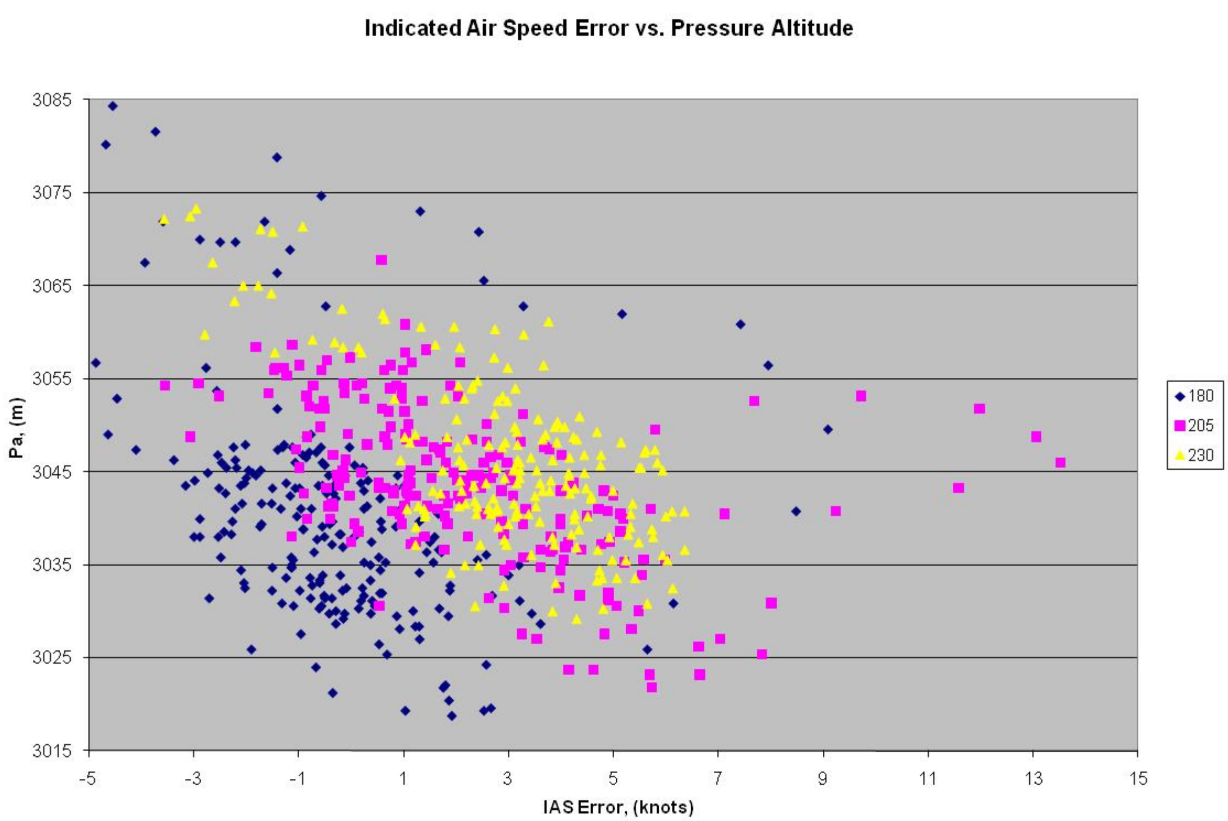

Figure 20 Indicated Air Speed Error vs Pressure Altitude at 3050 +/- 35 meters

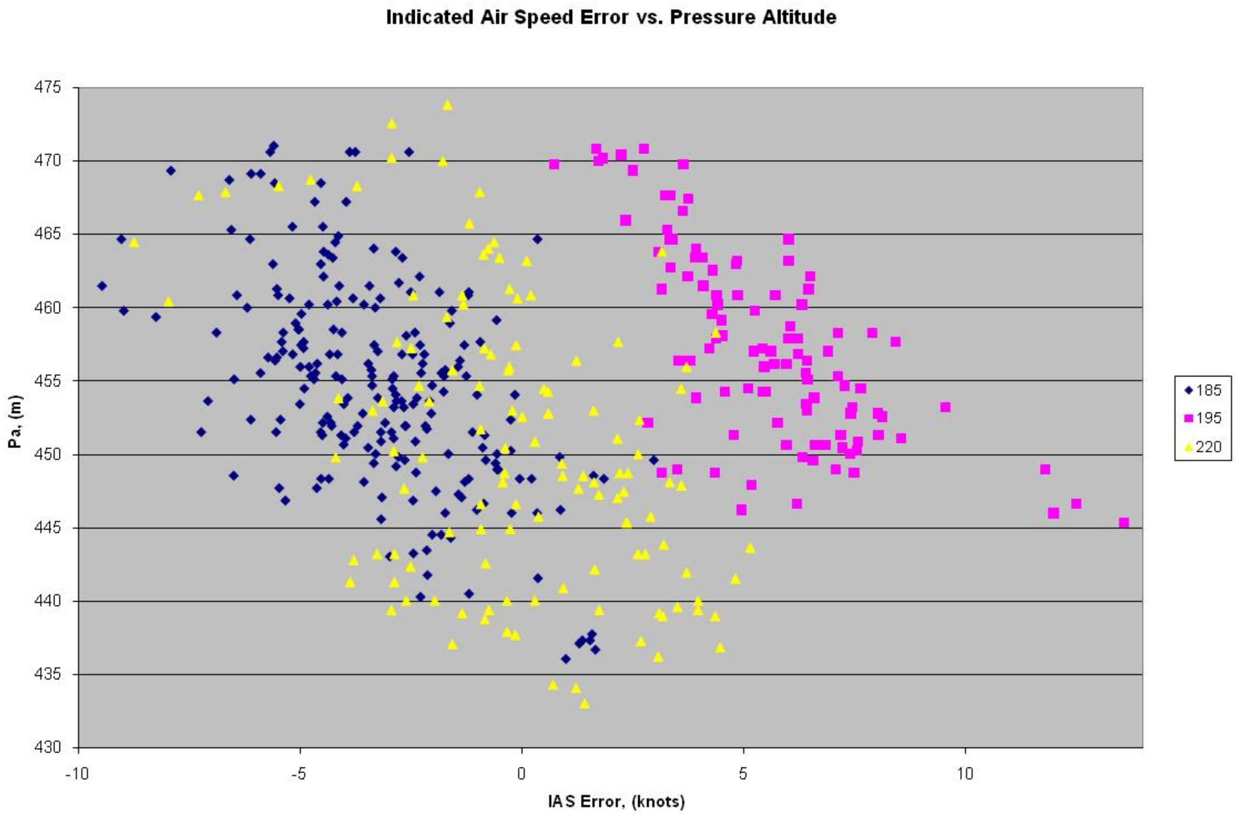

Figure 21 Indicated Air Speed Error vs Pressure Altitude at 452 +/- 22 meters

Table 9. Indicated Airspeed Validation Results

Indicated Airspeed (knots)									
Flight Segment	C1	C2	C3	C4	C5	C6	C7	C8	C9
Mean Error	-2.111	-2.192	-2.032	-0.581	1.643	2.811	-3.293	5.473	-0.004
Stan. Dev. Error	2.842	2.555	2.797	2.480	3.067	2.115	2.690	2.498	3.092
Minimum	-11.22	-10.54	-12.11	-7.451	-6.224	-3.575	-13.71	-1.486	-8.753
Maximum	7.196	7.410	9.215	9.086	13.523	7.653	3.734	14.850	7.719

The results of pressure altitude data analysis for each of the nine flight segments are listed in Table 10. Continuing the previous example, analysis of pressure altitude data for flight segment "C1" yields a mean error of -8.8 meters, a standard deviation of 18 meters, a minimum error of -71 meters, and a maximum error of 26 meters.

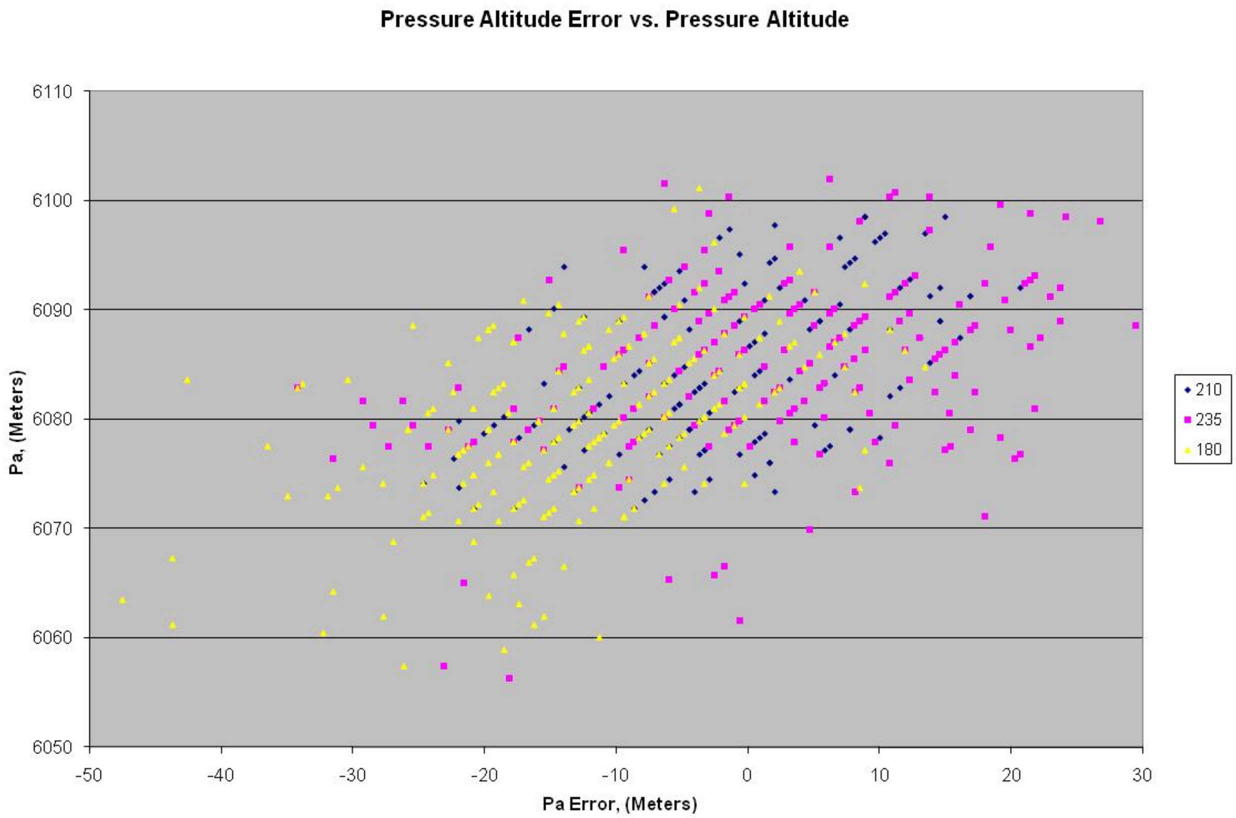

Figure 22 Pressure Altitude Error vs Pressure Altitude at 6080 +/- 30 meters

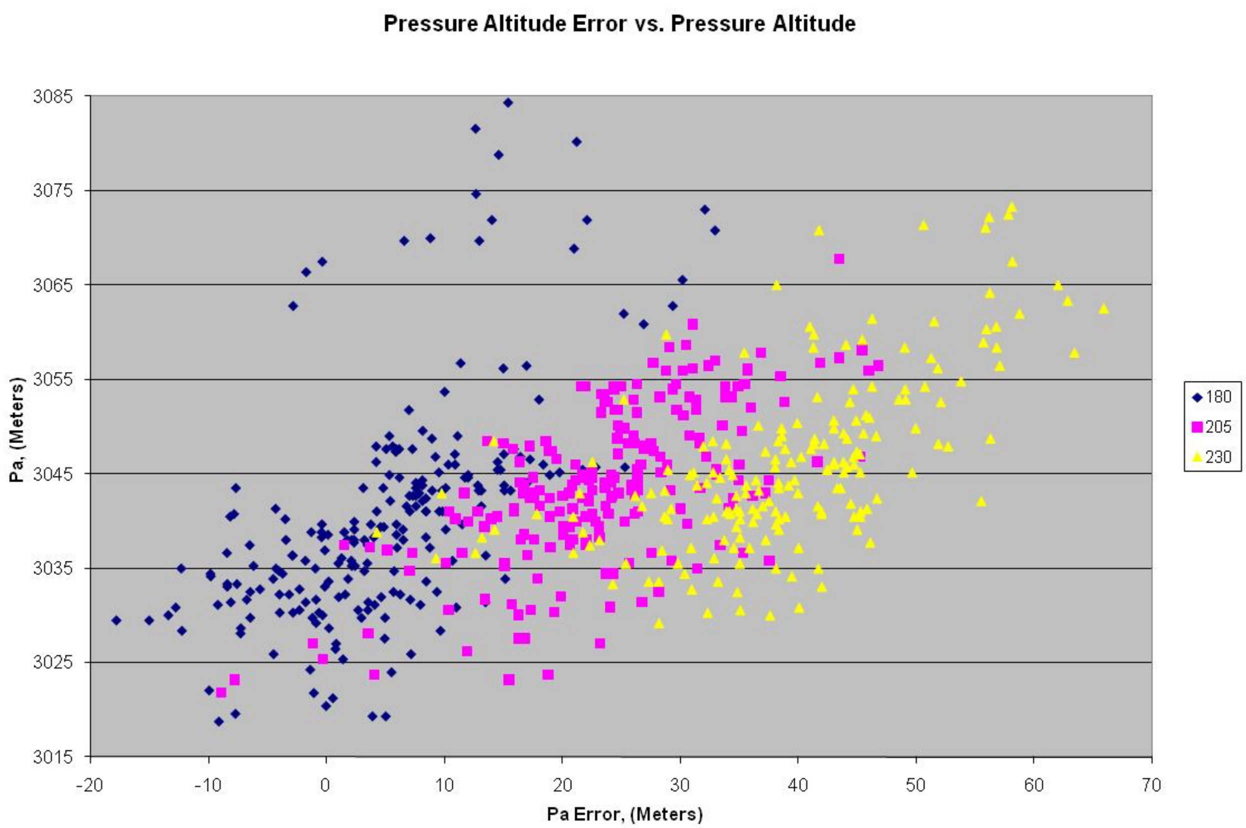

Figure 23 Pressure Altitude Error vs Pressure Altitude at 3050 +/- 35 meters

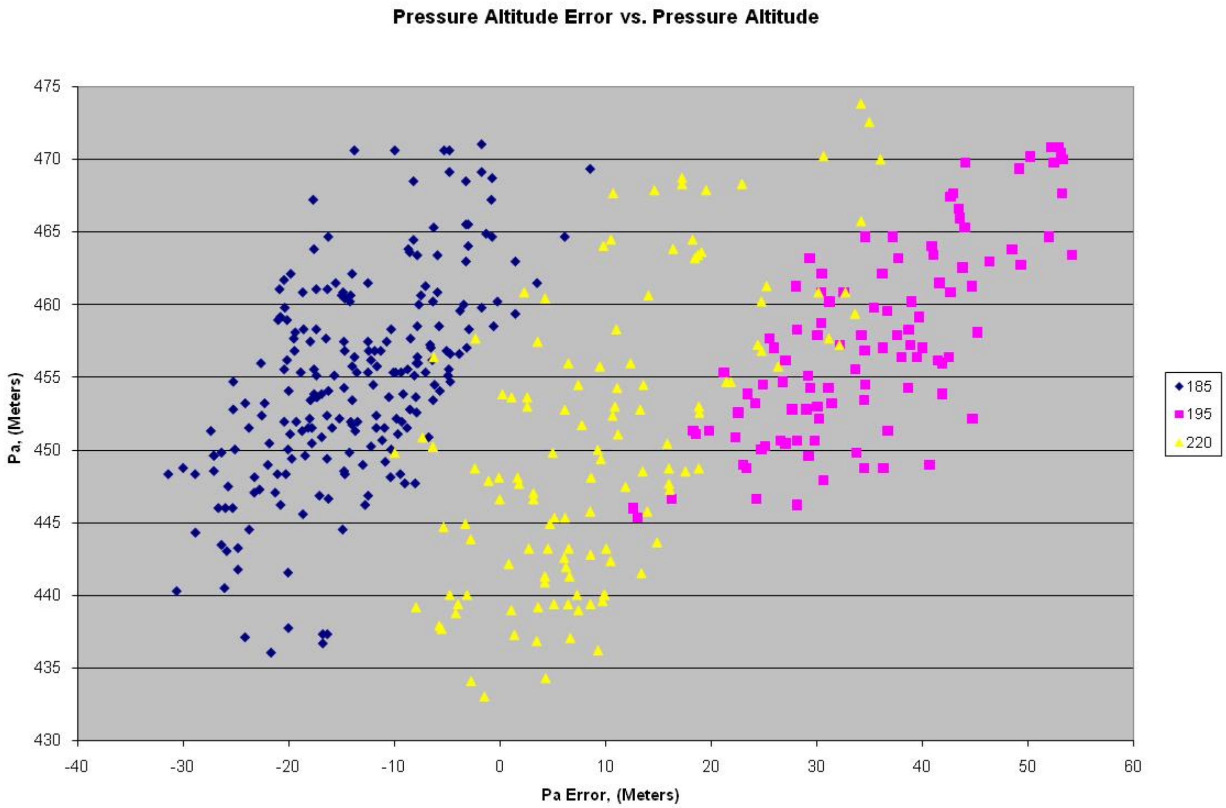

Figure 24 Pressure Altitude Error vs Pressure Altitude at 452 +/- 22 meters

Table 10. Pressure Altitude Validation Results

Pressure Altitude (meters)									
Flight Segment	C1	C2	C3	C4	C5	C6	C7	C8	C9
Mean Error	-8.833	-6.079	-11.87	2.267	22.00	37.25	-13.07	34.71	9.866
Stan. Dev. Error	18.05	21.78	15.88	11.28	10.37	11.89	10.19	8.27	12.25
Minimum	-71.51	-73.04	-50.78	-40.35	-11.06	3.371	-40.28	11.47	-29.39
Maximum	26.01	29.43	93.47	32.91	46.81	65.90	35.05	54.15	42.73

The results of wind direction data analysis for each of the nine flight segments are listed in Table 12. Continuing the previous example, analysis of wind direction data for flight segment "C1" yields a mean error of -2.4º, a standard deviation of 21º, a minimum error of -128º, and a maximum error of 39º.

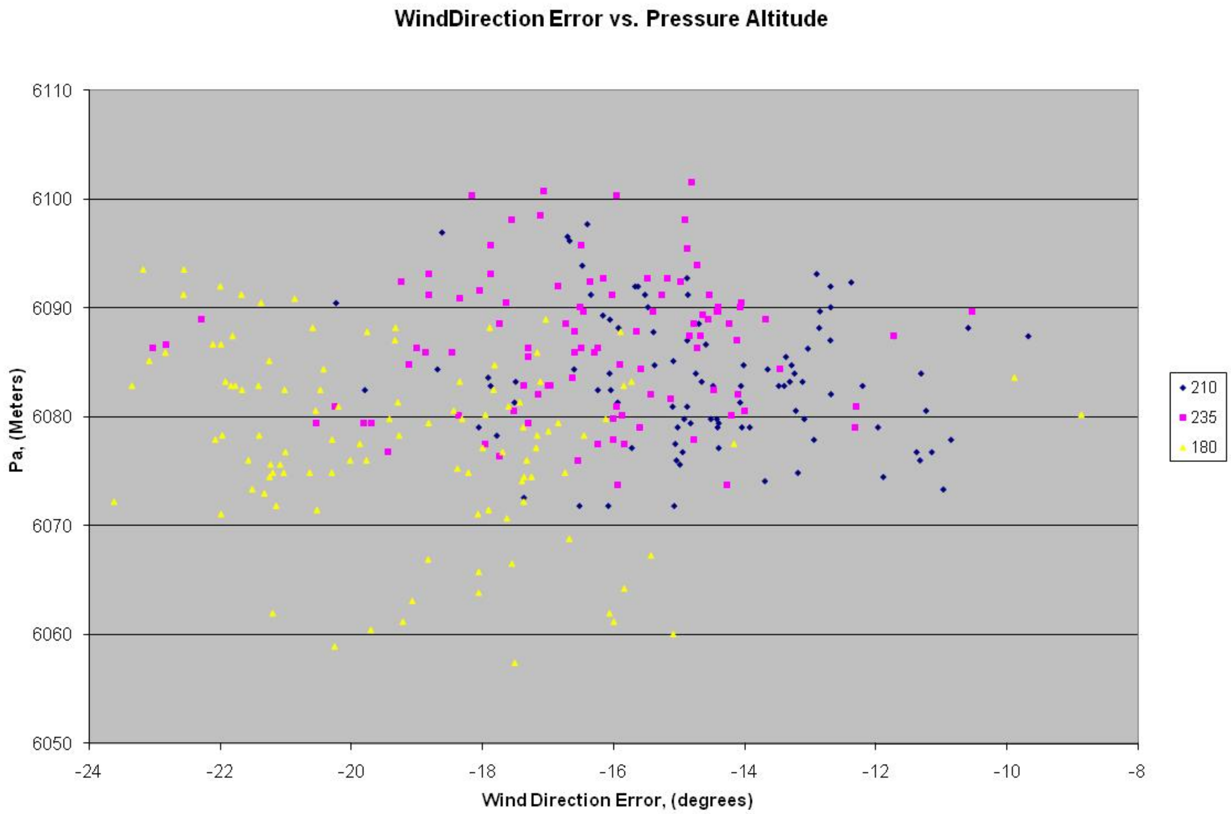

Figure 25 Wind Direction Error vs Pressure Altitude at 6080 +/- 30 meters

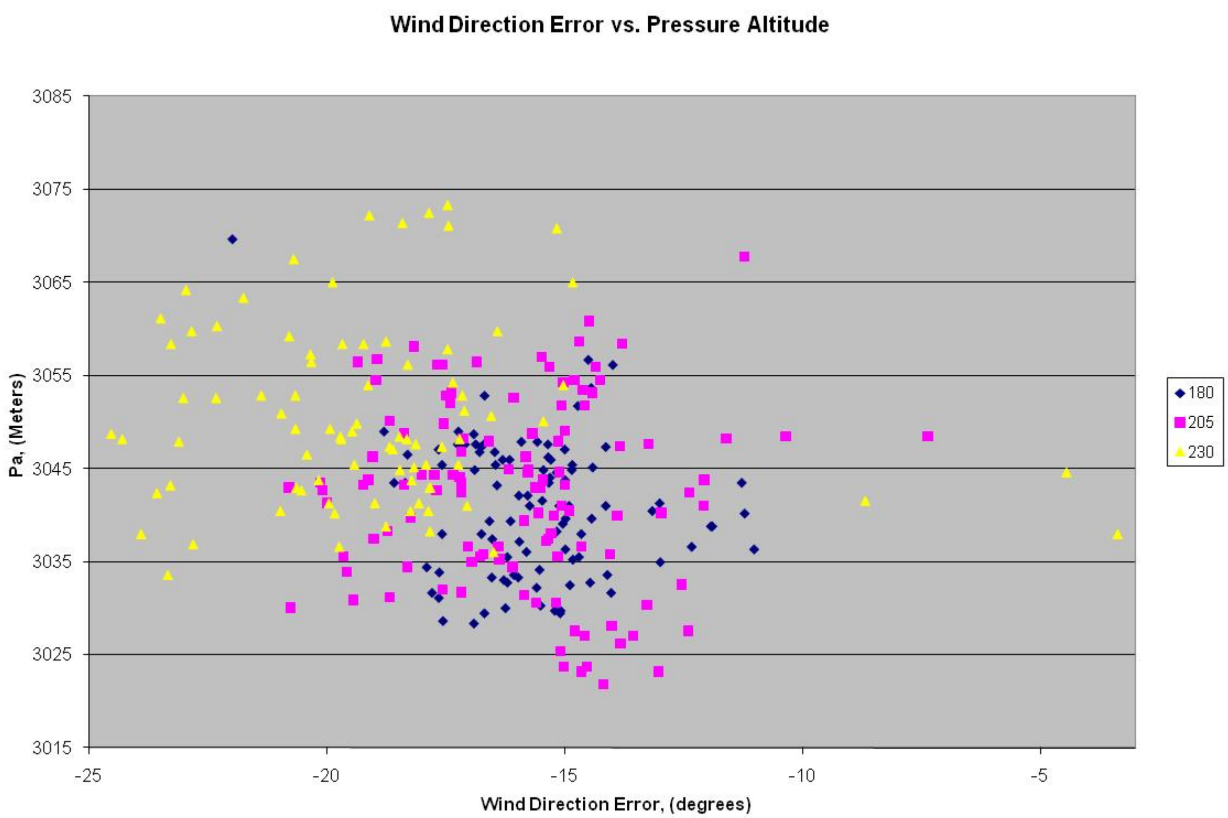

Figure 26 Wind Direction Error vs Pressure Altitude at 3050 +/- 35 meters

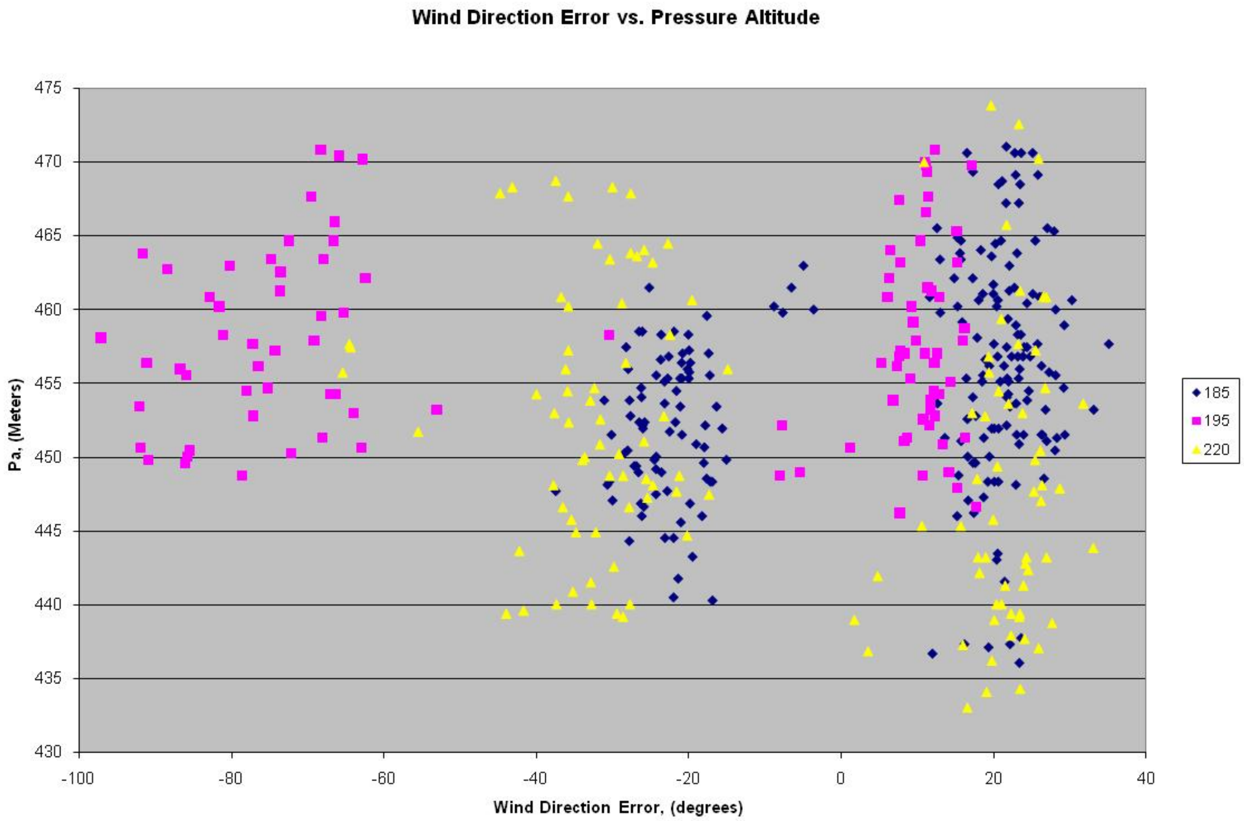

Figure 27 Wind Direction Error vs Pressure Altitude at 452 +/- 22 meters

Table 11. Wind Direction Validation Results

Wind Direction (degrees)									
Flight Segment	C1	C2	C3	C4	C5	C6	C7	C8	C9
Mean Error	-2.413	-4.702	-3.300	-0.758	-1.203	-0.536	2.654	-5.805	-4.463
Stan. Dev. Error	21.21	21.85	15.29	19.00	13.95	15.51	21.36	46.09	24.57
Minimum	-128.5	-142.1	-32.32	-138.3	-21.75	-51.35	-37.46	-104.8	-125.7
Maximum	39.33	25.52	19.75	21.65	18.62	21.13	35.14	66.36	33.03

The results of wind speed data analysis for each of the nine flight segments are listed in Table 12. Continuing the previous example, analysis of wind speed data for flight segment "C1" yields a mean error of -17.4 knots, a standard deviation of 4.4 knots, a minimum error of -25 knots, and a maximum error of 7.5 knots.

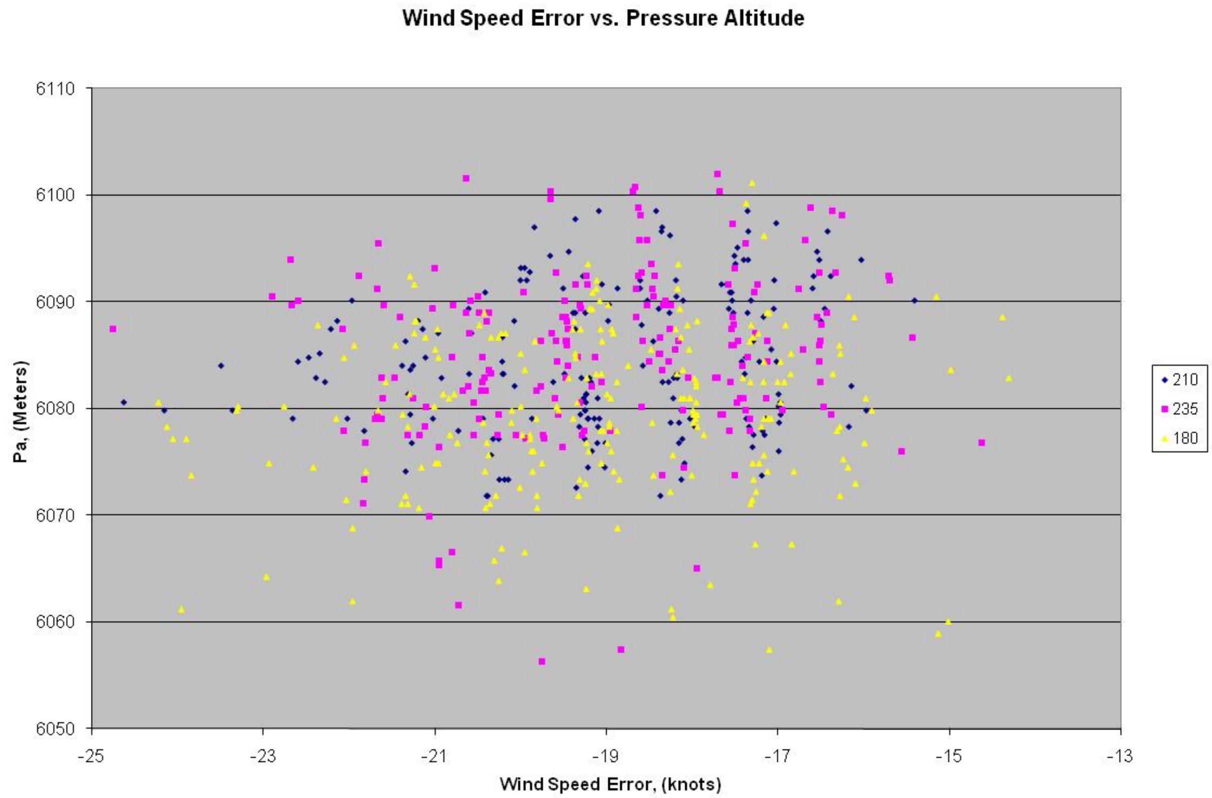

Figure 28 Wind Speed Error vs Pressure Altitude at 6080 +/- 30 meters

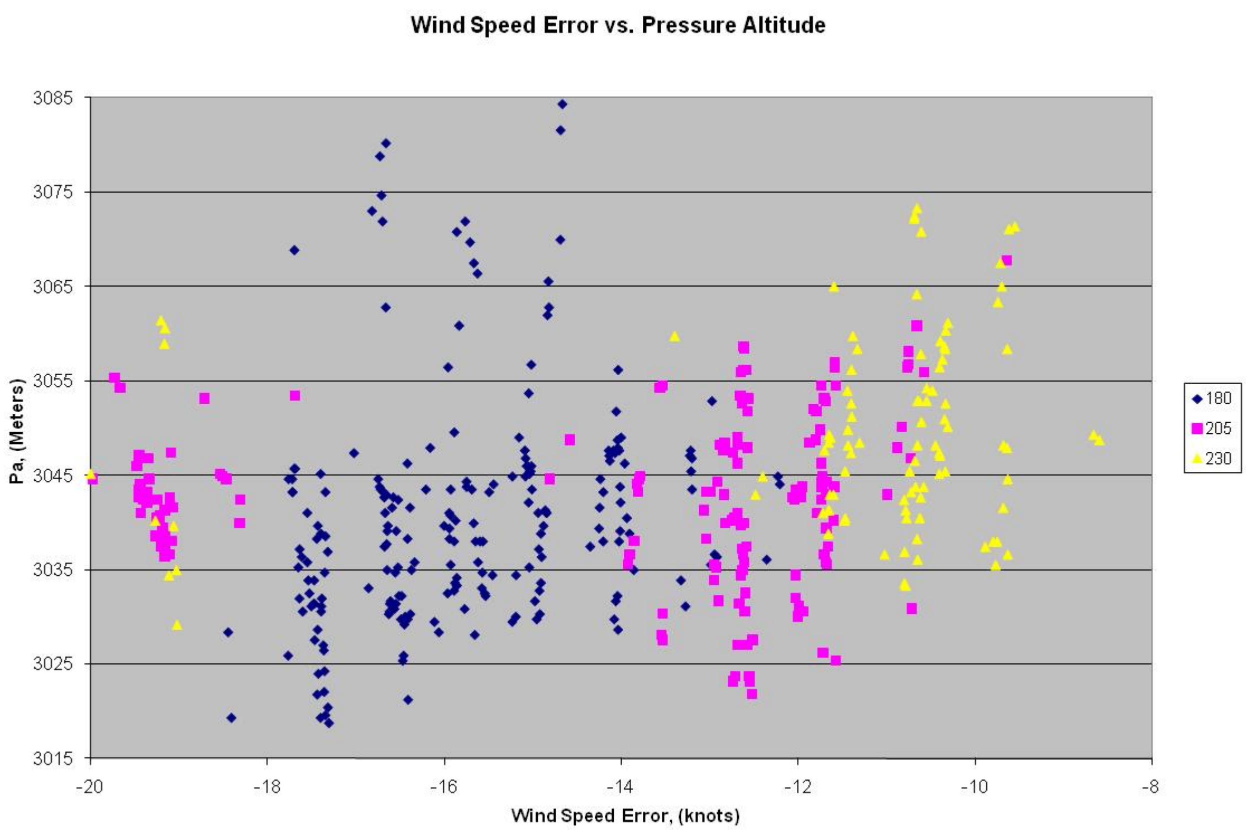

Figure 29 Wind Speed Error vs Pressure Altitude at 3050 +/- 35 meters

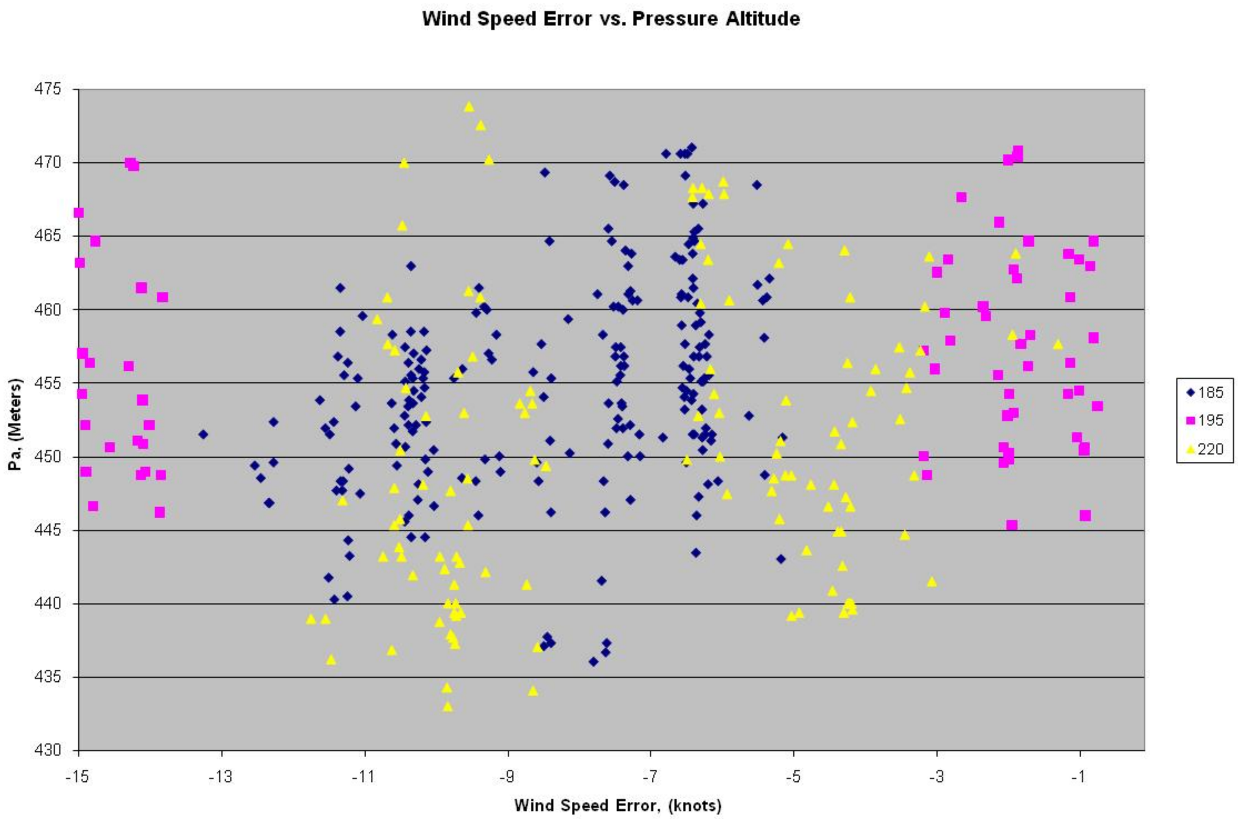

Figure 30 Wind Speed Error vs Pressure Altitude at 452 +/- 22 meters

Table 12. Wind Speed Validation Results

Wind Speed (knots)									
Flight Segment	C1	C2	C3	C4	C5	C6	C7	C8	C9
Mean Error	-17.38	-18.50	-19.84	-15.14	-15.98	-16.75	-8.171	-7.846	-6.543
Stan. Dev. Error	4.433	3.724	2.499	2.559	3.701	5.156	1.979	5.292	3.420
Minimum	-25.59	-29.42	-29.68	-18.44	-22.50	-24.27	-13.25	-16.23	-12.09
Maximum	7.482	-5.155	-14.31	-4.075	-8.887	-8.597	-3.927	2.246	-1.219

Sounding Validation Results

As the intended function of the TAMDAR sensor is to collect meteorological data, actual use will include the collection of soundings. The WP-3D validation test flight included time segments of data collected during changing altitude. The aircraft transitioned from 460 m to 3050 m and 6100 meters and back down, and in doing so, collected four segments of sounding data. The details of these four segments are listed in Table 13. For convenience, each sounding segment is labeled “S1”, “S2”, etc. These labels are used in subsequent tables of data analysis to refer to these specific flight segments. Only obviously errant data points were eliminated for the error analysis. The flight data was analyzed by comparing the temporal TAMDAR data with the WP-3D reference data.

Table 13. Sounding Details

Sounding Segment	S1	S2	S3	S4
Average IAS (kts)	205	188	186	196
Altitude Change (m)	+2590	+3050	-3050	-2590
Aircraft Heading	Straight	Turn	Spiral	Turn
Number of Obs	123	213	232	178

Analysis was performed for each sounding by comparing each TAMDAR parameter (with the exception of turbulence and icing) with the corresponding WP-3D values. Comparison data was time synchronized prior to differencing to yield error values. The mean and the standard deviation of each error set for each flight segment was then computed. The flight segment "S1" had 123 data points for comparison. This data set was recorded while the WP-3D was flying at airspeed of 205 knots, changing altitude from 460 meters to 3050 meters, and heading into the wind direction. The flight segment "S2" was recorded with aircraft heading along the wind direction and ending with a 180º turn, as the altitude changed from 3050 meters to 6200 meters. The flight segment "S3" was recorded with aircraft initially heading into the wind direction and then descending in a series of 90º turns, as the altitude changed from 6200 meters to 3050 meters. The flight segment "S4" was recorded with aircraft heading along the wind direction and ending with a 180º turn as the altitude changed from 3050 meters to 460 meters.

The results of temperature data analysis for each of the four soundings are listed in Table 14. Analysis of temperature data for flight segment "S1" yields a mean error of 0.54 ºC, a standard deviation of 0.76ºC, a minimum error of -1.5 ºC, and a maximum error of 2.0 ºC.

Table 14. Temperature Sounding Results

Temperature (ºC)				
Sounding Segment	S1	S2	S3	S4
Mean Error	0.5436	0.8171	-0.2962	-0.6401
Std. Dev. Error	0.7580	0.3248	0.1976	0.5106
Minimum Error	-1.499	-0.1362	-0.7734	-1.554
Maximum Error	1.964	1.535	0.2032	0.5892

The results of relative humidity data analysis for each of the four soundings are listed in Table 15.

Table 15. Relative Humidity Sounding Results

Relative Humidity (%)				
Sounding Segment	S1	S2	S3	S4
Mean Error	-1.545	-4.662	-3.147	-2.103
Std. Dev. Error	2.598	1.827	1.636	3.095
Minimum Error	-3.209	-7.213	-7.447	-11.87
Maximum Error	12.01	0.3724	-0.8215	3.958

The results of indicated airspeed data analysis for each of the four soundings are listed in Table 16.

Table 16. Indicated Airspeed Sounding Results

IAS (knots)				
Sounding Segment	S1	S2	S3	S4
Mean Error	0.3146	-1.323	-0.3364	3.434
Std. Dev. Error	6.253	5.520	3.888	3.636
Minimum Error	-12.30	-13.11	-13.52	-3.733
Maximum Error	18.13	11.71	12.01	13.15

The results of pressure altitude data analysis for each of the four soundings are listed in Table 17.

Table 17. Pressure Altitude Sounding Results

Pressure Altitude (meters)				
Sounding Segment	S1	S2	S3	S4
Mean Error	-147.9	-113.9	75.62	105.9
Std. Dev. Error	74.83	51.44	34.49	63.35
Minimum Error	-247.0	-234.6	-16.11	-16.92
Maximum Error	34.28	5.055	143.4	195.4

The results of wind direction data analysis for each of the four soundings are listed in Table 18.

Table 18. Wind Direction Sounding Results

Wind Direction (degrees)				
Sounding Segment	S1	S2	S3	S4
Mean Error	-21.68	13.81	-5.504	-17.12
Std. Dev. Error	10.78	4.033	10.36	12.12
Minimum Error	-48.15	-4.452	-21.63	-55.63
Maximum Error	3.452	22.11	23.08	11.59

The results of wind speed data analysis for each of the four soundings are listed in Table 19.

Table 19. Wind Speed Sounding Results

Wind Speed (knots)				
Sounding Segment	S1	S2	S3	S4
Mean Error	-12.88	-20.98	-17.31	-10.62
Std. Dev. Error	4.170	2.185	4.537	5.490
Minimum Error	-19.97	-29.41	-27.50	-26.98
Maximum Error	-1.490	-16.17	-6.636	-0.7976

Comparisons to Dropsonde

The TAMDAR sensor data will be compared to rawinsonde data in future validation studies. As an initial comparison, the TAMDAR temperature, relative humidity, and winds are compared to the data from a dropsonde. A Vaisala TM model RS90 dropsonde was released, while the WP-3D was flying at an altitude of 6100 m and at airspeed of 210 knots at the end of "C1", but prior to the increase in airspeed for "C2". Only the dropsonde and TAMDAR data measured at the same altitude are compared. The same flight segments used in the sounding comparisons was also used for the dropsonde comparisons. As a result, the same number of data points was analyzed in each of the four segments. The comparison results are listed in tables 20 through 23.

Table 20. Temperature Dropsonde Comparison Results

Temperature (ºC)				
Sounding Segment	S1	S2	S3	S4
Mean Error	-0.4732	-0.2081	0.1154	-0.2986
Std. Dev. Error	0.6371	0.8379	0.2410	0.6225
Minimum Error	-2.21	-1.3	-0.34	-2.55
Maximum Error	0.19	1.96	0.86	0.66

Table 21. Relative Humidity Dropsonde Comparison Results

Relative Humidity (%)				
Sounding Segment	S1	S2	S3	S4
Mean Error	-6.561	-10.32	-7.023	-6.789
Std. Dev. Error	4.8070	6.366	4.117	6.662
Minimum Error	-21.7	-22	-21	-24.28
Maximum Error	3.59	0.72	-0.05	15.45

Table 22. Wind Direction Dropsonde Comparison Results

Wind Direction (degrees)				
Sounding Segment	S1	S2	S3	S4
Mean Error	-23.30	5.262	-5.872	-20.07
Std. Dev. Error	8.781	7.811	12.99	12.84
Minimum Error	-42.5	-12.73	-30.60	-46.97
Maximum Error	1.53	22.24	29	4.81

Table 23. Wind Speed Dropsonde Comparison Results

Wind Speed (knots)				
Sounding Segment	S1	S2	S3	S4
Mean Error	-8.232	-17.01	-11.86	-5.791
Std. Dev. Error	3.620	3.001	3.918	4.857
Minimum Error	-14.55	-25.22	-21.18	-22.59
Maximum Error	1.01	-9.73	-3.1	1.03

PERFORMANCE SUMMARY

Table 24 summarizes the statistics of the probe performance relative to the P3 reference instrumentation. With the exception of icing, these results are within the desired specifications found in Table 1.

Parameter		RMS error	Bias	Standard deviation	TAMDAR target requirements
Pressure altitude (feet)		21.7	-6.4	20.7	+/- 45.7 m
TAS (knots)		1.9	0.05	1.9	+/- 4 knots
IAS (knots)		1.59	-0.028	1.59	+/- 3 knots
Temperature (C)		0.33	0.073	0.32	+/- 1 deg C
Relative humidity (%)	All data:	3.7	2	3.1	Not specified
	Mach<0.4:	*	*	*	+/- 5% < Mach 0.4
	Mach 0.4-0.6:	*	*	*	+/- 10% Mach 0.4-0.6
Winds aloft vector magnitude	No Heading offset	2.5	NA	2.5	+/- 6 knots
	0.985 deg heading offset (post-processed)	2.3	NA	2.3	-

(Note: *= Not Calculated.)

Error Statistics For Mission. (TAMDAR And P3 Data Set: 50268 To 64589 SFM).

Discussion and Conclusions

The performance summary statistics in Table 24 indicates acceptable performance throughout the whole flight regime, on the entire range of conditions envisioned for the TAMDAR sensor.

Although no turbulence information is included in the WP-3D reference data, if such data are needed to be collected in the future, the TAMDAR sensor processor will require a DSP to reduce the background “noise” level.

Periodic wind direction errors synchronous with the racetrack patterns were noted. Assuming that an offset in the heading supplied to TAMDAR from the WP-3D system could account for the heading errors, the winds aloft data were post-processed, and an offset of –0.985 degrees was added to the heading. The addition of this offset brought the TAMDAR wind direction significantly closer to the WP-3D reference. It should be mentioned that the wind direction and the wind speed errors alone are not consistent parameters to characterize the instrument performance, because, they depend heavily on unsteady atmospheric conditions. For example, the racetrack patterns flown into and away from the wind, as was the case with the WP-3D, would result in greater direction errors than if they were done perpendicular to the wind. Low wind speeds in the former case would result in greater direction errors than high wind speeds. It is for this reason that the magnitude of the wind error vector is the preferred measurement of accuracy. This is the method used in the AMDAR Reference Manual, 2003. It should also be noted that the WP-3D data exhibited the same periodicity effect with the racetrack pattern, implying that it may also have errors.

Experience has shown that if care is taken on the probe location selection, and if the results are analyzed to produce accurate calibration constants that are then uploaded to the TAMDAR sensor, excellent results are obtained in subsequent flights. This somewhat tedious process needs to be done only once for a given aircraft and configuration.

These flight tests demonstrated TAMDAR's ability to serve as an accurate meteorological instrument for the measurement of temperature, pressure altitude, relative humidity, and winds aloft. Turbulence and icing performance could not be verified on these flights because of the lack of reference data and icing conditions.

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5. A. Barry Damiano and Richard J. McNamara, "Navigational and Meteorological Variables Measured and Derived by NOAA/AOC WP-3D Aircraft", (To be published).

6. James Roles, NOAA WP-3D Chief Engineer, personal communication, May 2005.

APPENDIX

NOAA/AOC WP-3D STANDARD INSTRUMENTATION						
Parameter Measured	Instrument Type	Manufacture & Model Number	Range	Resolution[#]	Accuracy	Response Time
Aircraft Position[β@] (lat,lon)	Differential GPS	Ashtech DGPS BRG2	Dependent on Beacon coverage	0.185m (lat,lon)	2m (lat,lon)	10/s
	2 Independent Inertial Navigation Systems	Delco Carousel IVA	Worldwide	0.00009° (lat,lon)	1 nmi/hr drift RMS	40/s
	5 Channel GPS Precision (Y Code)	Rockwell Receiver 3M	Worldwide	lat. 0.76m lon. 1.14m	16m SEP	1/s
Aircraft Velocity[β]			680 knot	East 0.023 knot North 0.023 knot Up 0.023 knot	0.2 knot	
Pitch[β]	Wander Azmith Stable Platform Inertial Reference System	Delco Carousel IVA	± 90°	0.0001°	0.06°	40/s
Roll[β]			± 90°	0.0001°	0.06°	
Drift Angle[β]			± 90°	0.0001°	0.1°	
Heading[β]			0 to 360°	0.0001°	0.1°	
East Velocity[β]			± 1555 knot	0.0004 knot	1 knot	
North Velocity[β]			± 1555 knot	0.0004 knot	1 knot	
Ground Speed[β]			0 to 1555 knot	0.0004 knot	1 knot	
Track Angle (comp)			0 to 360°	0.0001°	0.2°	
Static Pressure	Ps Transducer (Wingtip Pitot)	Rosemount 1281AF1B2B Static (Ps) and Dynamic (qc) Transducer	250 to 1050 mb	0.024 mb	± 1.6 mb[σ]	15 ms maximum
	Ps Transducer (Fuselage Pitot)					
Dynamic Pressure	qc Transducer (Wingtip Pitot)		0 to 165 mb	0.005 mb	± 0.53 mb[σ]	15 ms maximum
	qc Transducer (Fuselage 1)					
	Differential Pressure Transducer (Fuselage 2)	Rosemount 1221F1AF1B1B	0 to 345 mb	0.01 mb	± 1.1 mb[σ]	10 ms* maximum
Angle of Attack Differential Pressure	Differential Pressure Transducer	Rosemount 1221F2VL7B1B	0 to ± 69 mb	0.002 mb	0.22 mb[σ]	10 ms* maximum
Sideslip Differential Pressure						
Angle of Attack Dynamic Pressure	Differential Pressure Transducer	Rosemount 1221F2AF7B1B	0 to 170 mb	0.005 mb	0.55 mb[σ]	10 ms* maximum
Sideslip Dynamic Pressure						
Radome Angle of Attack Differential Pressure	Differential Pressure Transducer	Rosemount 1221F1VL7B1B	0 to ±69mb	0.002mb	±0.19mb[σ]	10ms* Maximum
Radome Sideslip Differential Pressure						

NOAA/AOC WP-3D STANDARD INSTRUMENTATION

Parameter Measured	Instrument Type	Manufacture & Model Number	Range	Resolution[#]	Accuracy	Response Time
Radome Dynamic Pressure		Rosemount 1221F1AF1B1B	0 to 345mb	0.01mb	± 1.1mb[σ]	10ms* Maximum
Radome Impact Pressure	Precision Absolute Pressure Transducer	Rosemont 1201F2A14A1A	0 to 1150mb	0.07mb	± 3.1mb[σ]	15ms Maximum
Total Temperature	Deiced Platinum Wire Resisitor	Rosemount 102CH2AF w/510DY	-60°/+60°C	0.002°C	± 0.6°C	1.5s[&]
		Rosemount 102CP2AF w/510GB41E	-70°/+70°C	0.002°C	± 0.7°C	1.5s[&]
	Non - Deiced Platinum Wire Resisitor	Rosemount 102E4AL w/510GB35E	-50°/+50°C	0.002°C	± 0.4°C	1.0s[&]
Sea Surface Temperature	IR Radiometer (9.5-11.5 µm)	Barnes Model PRT-5 w/ AOC Control Units	-20°C / +40°C	0.003°C	0.5°C	40ms
CO_2 Absorption Temperature	IR Radiometer (14-16 µm)		-40°C / +30°C	0.003°C	1.0°C	1.5s
Upward Looking Temperature	IR Radiometer (Selectable)		Selectable (-75 / +40°C)	0.003°C	0.5°C	40ms
Dewpoint Temperature[@]	Chilled Mirror Hygrometer	General Eastern 1200EP w/ 1011B-SI Sensor	-75°C to +50°C	0.003°C	± 0.5°C**	2°C/s**
		EdgeTech 137-C3	-100°C to +50°C	0.009°C	± 0.5°C**	2°C/s**
	Spectral Absorption	Lyman-Alpha Hygrometer	-80°C to +50°C	0.003°C	± 0.5°C	2 ms
Cloud Liquid Water	Resistance Wire	Johnson Williams LWH	0-6 gm/m^3	0.001gm/m^3	± 10%	1 s
	Hot Wire	PMS King Liquid Water				
Visible Radiation (0.3-5µm) Short-wave	Up-looking Pyranometer	Eppley PSP	0-2800 Wm^{-2}	Contact AOC/SED	± 1% over -20 to +40°C Range	1 s
	Down-looking Pyranometer					
Infrared Radiation (4-50µm) Long-wave	Up-looking Pyrgeometer	Eppley PIR	0-700 Wm^{-2}		± 2% over -20 to +40°C Range	2 s
	Down-looking Pyrgeometer					
True Altitude[β]	Radar Altimeter	Stewart Warner APN159	15,000 m	1 meter	Greater of 3m or ±1% Full Scale	
		Gould APN-232		0.1 meter	±2% of Altitude	1 s Full Scale
Geopotential Altitude[β]	5 Channel GPS Precision (Y Code)	Rockwell Receiver 3M	Worldwide	MSL 12µm ABS 12µm	16m SEP	1 s
Horizontal Radar Reflectivity[α]	Nose PPI C-Band[δ]	Collins WRT-701C	180°(horiz) Azmith 320 nmi ±40° elev	5.4°x 5.4° beam		PRF 400 at 3µs
	Lower Fuselage C-Band Color Weather Radar	AOC, Videotronics,	360°(horiz) Azmith 200 nmi ±10° elev	1.1°x 4.1° beam		PRF 200 at 6µs

NOAA/AOC WP-3D STANDARD INSTRUMENTATION						
Parameter Measured	Instrument Type	Manufacture & Model Number	Range	Resolution[#]	Accuracy	Response Time
Vertical Radar Reflectivity[α]	Color Doppler X-Band Radar	Sigmet	360°(vert) Azmith 50 nmi perp. to track ±22.5°(fwd-aft)	1.4°x 1.9° beam	±25.0 - ±72.0 knots before folding	PRF 1600-3200 at 0.5-0.25μs
Meteorological and Atmospheric Sensor Output	Data Acquisition System	AOC, Hewlett Packard	-10V to +10V	16 bit (Averaged)	±1 lsb	1 sample/s
				15 bit (Averaged)	±1 lsb	10, 20 sample/s
				14 bit	±1 lsb	40, 80 sample/s

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14. ABSTRACT
As part of the National Aeronautics and Space Administration's Aviation Safety and Security Program, the Tropospheric Airborne Meteorological Data Reporting project (TAMDAR) developed a low-cost sensor for aircraft flying in the lower troposphere. This activity was a joint effort with support from Federal Aviation Administration, National Oceanic and Atmospheric Administration, and industry. This paper reports the TAMDAR sensor performance validation and verification, as flown on board NOAA Lockheed WP-3D aircraft. These flight tests were conducted to assess the performance of the TAMDAR sensor for measurements of temperature, relative humidity, and wind parameters. Summary results from the flight test are presented along with corroborative data from aircraft instruments.

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Aircraft safety; Aircrft instruments; Flight tests; TAMDAR

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