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The Development of a New Anemometer for Measuring High Speed Winds on Mount Washington, New Hampshire

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THE DEVELOPMENT OF A NEW ANEMOMETER FOR MEASURING HIGH SPEED WINDS ON MOUNT WASHINGTON, NEW HAMPSHIRE

By

Mark W. Thoren

B.S. University of Maine, 1996

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Electrical Engineering)

The Graduate School

The University of Maine

May, 2001

Advisory Committee:

Richard Eason, Associate Professor of Electrical Engineering, Advisor
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Bruce E. Segee, Associate Professor of Electrical Engineering
Michael Boyle, Associate Professor of Mechanical Engineering

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THE DEVELOPMENT OF A NEW ANEMOMETER FOR MEASURING HIGH SPEED WINDS ON MOUNT WASHINGTON, NEW HAMPSHIRE

By Mark W. Thoren

Thesis Advisor: Dr. Richard Eason

An Abstract of the Thesis Presented
in Partial Fulfillment of the Requirements for the
Degree of Master of Science
(in Electrical Engineering)
May, 2001

Mount Washington, NH is well known as the "Home of the Worlds Worst Weather." Winds on the mountain regularly exceed 100 miles per hour, the record being 231 mph on April 12, 1934. There is a long history of weather observation on the mountain that has included various recording techniques. Until recently, the primary means of recording data has been paper strip charts. This project represents significant improvements to the Observatory's instrumentation system.

Measuring windspeed on Mount Washington presents a number of design challenges. Any instruments directly exposed to the weather must be very durable. Fortunately this problem had been solved and allowed attention to be focused on the instrumentation. The challenge then becomes ensuring the accuracy and reliability of measurements taken

from the instruments. This involves electrical interfacing concerns and decisions about how best to distribute the computation of the collected data.

The part of this work that was the biggest success is the hardware. For the first time, the Observatory has research grade instruments for measuring and recording windspeed, barometric pressure and temperature and a proper error analysis on each instrument.

ACKNOWLEDGEMENTS

I would like to thank Professor Jill Schoof for giving me the opportunity to return to school to work on this unusual and exciting project. I would also like to thank Ken Rancourt, research director at the Mount Washington Observatory, Tod Hagan, Sarah Curtis and the rest of the Mount Washington Staff for their input and assistance throughout the project.

Finally, I would like to thank the other members of my committee: Professor Michael Boyle of Mechanical Engineering who taught me some of the fundamental concepts I used in this project when I was a Bio-Resource Engineering student, and Professor Richard Eason and Professor Bruce Segee of the Department of Electrical and Computer Engineering who helped me to have an excellent experience as an Electrical Engineering student.

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Chapter 1

Introduction

Mount Washington, New Hampshire has many claims to fame, most notable of which is its reputation as "Home of the World's Worst Weather" which is based on the record 231 mile per hour gust recorded on April 12, 1934. This is the highest windspeed ever measured by man on earth. This measurement was made with a rotating anemometer that was recalibrated by the National Bureau of Standards after the event to confirm its accuracy[1].

Anemometers at the observatory since then have varied in type and accuracy. In January of 1999, a project commenced to evaluate and update the anemometry system. This thesis is the result of that work.

Accurate windspeed measurement at the summit of Mount Washington is essential for a number of reasons. Although not many people are directly affected by weather at the summit, many experiments take place that require various weather parameters for their data analysis. A few examples of equipment that has been tested at the summit are icing detectors, fog detectors, anemometers, and atmospheric pollution instruments. In addition, one cannot deny that knowledge of the natural world is inherently interesting, especially in a place with which such superlatives are associated.

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[1] McKenzie, Alexander. World Record Wind. Center Ossipee, NH: Carroll County Independent, 1984. p25.

1.1 Thesis Objectives

The goal of this work was to design, construct and install a new Pitot measurement system in the Mount Washington Observatory (MWO). The present system is antiquated and in need of upgrade. Design goals are that the system be simple, accurate and flexible and able to archive data over the Observatory's computer network.

This project involves several engineering disciplines. The quantities being measured are mechanical in nature. Sensors needed to be carefully selected, the analog outputs from the sensors need to be digitized, windspeed needs to be calculated from the basic measurements, and the data must be collected and archived. Another aspect of this project was to evaluate the existing system for the purpose of evaluating the accuracy of past data.

1.2 Background

Since the 1930's a Pitot-static anemometer has measured windspeed and barometric pressure on the observatory's towers. The Pitot tube anemometer has two attributes that set it apart. One is that its use as a barometer is essential for compensating for pressure deficiency due to orographic wind (see section 1.4). This necessitates the use of a Pitot tube even if another instrument is used to measure windspeed. A second attribute is that the probe has a built-in 140 watt heater that prevents ice from forming[2]. Pitot tubes are commercially available that are designed to operate on aircraft at speeds greater than Mach 1 and in very low temperatures. Such aircraft Pitot tubes will not ice up when properly installed at the observatory. Aside from being well suited to the extreme icing at Mount Washington, the Pitot anemometer is an outstanding choice for this anemometry application.

In his book Ten Years on the Rock Pile, Lee Vincent gives a rather humorous, if erroneous, statement about the Pitot tube:

> "The old Pitot tube theme is no longer any good, except that it is easy to keep clean of ice and for that, in my opinion is why it is still used. I wish they would get rid of it and stop being like old Yankees, hard to convince that what was good enough for their fathers is not necessarily what is good for them, that there are technical advances and they should keep pace.[3]"

He does not suggest an alternative.

Excluding exotic measurement devices such as laser doppler and ultrasonic anemometers, there are only a few basic ways to measure how fast air is moving. Advances in electronic measurement have certainly made existing anemometers more accurate, but the basic principles are the same. This chapter will detail the reasons that a Pitot-static anemometer is still the best choice for the Observatory.

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[2] Aero Instrument Company, inc. Catalog. Cleaveland, OH: p6.

[3] Vincent, Lee. Ten Years on the Rockpile. Gorham, NH: Rockpile Publications, 1973. p7.

1.3 State of the Art of Commercial Anemometers

At the University of Maine, a survey of commercial anemometers was conducted, and the conclusion is that there are no commercial anemometers suitable for winter use at Mount Washington Observatory. Commercial units are generally not calibrated above 160 mph and many are vulnerable to destruction by winds above 60 mph. Inadequate heat is a problem in all units available. The most reliable anemometer in terms of reliability and ability to prevent ice formation is "Pitot 92," which was installed in 1992 and has been in service almost continuously and is still in service at the time of this writing. This unit is very rugged and has proven its ability to remain relatively ice free in the worst conditions. A complete discussion of the Pitot tube and vane assembly is beyond the scope of this thesis, which will focus on the actual windspeed measurements.

Standard anemometers for meteorological use are usually of the familiar propeller or cup type. See Figure 1.1. The World Meteorological Organization has guidelines for the performance of anemometers.[4] Basic accuracy should be 10% or better with a linearity of +/- 0.5 m/s (1.12 mph) over a range of 0.5 to 75 m/s (167 mph.) Unfortunately, such anemometers are unsuitable for use on Mount Washington due to the constant high winds and severe icing.

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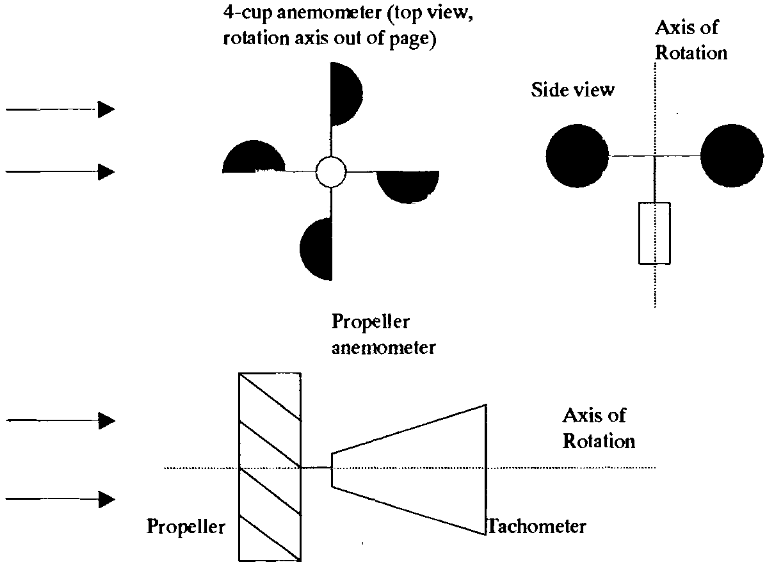
[4] Guide to Meteorological Instruments and Methods of Observation, 6th ed. Geneva, Switzerland: World Meteorological Organization, 1996. pI.5-3.

Figure 1.1 Propeller and Cup Anemometers



Before describing the qualifications of the pitot anemometer, we will first review some of the other types of anemometers in existence. Focus 2000: Wind, Ice and Fog, the proceedings of the fourth annual Mount Washington Observatory symposium, describes a comparison between three heavy-duty anemometers in freezing rain conditions[5]. Key features of these instruments are summarized in the following sections.

The first is an R.M. Young brand helicoid anemometer. This is a modification of the basic "propeller" style anemometer described previously. It is described as a primary measurement unit, meaning it is affected by the parameter being measured and nothing else. (Another example of a primary measurement is a mercury barometer because the

---

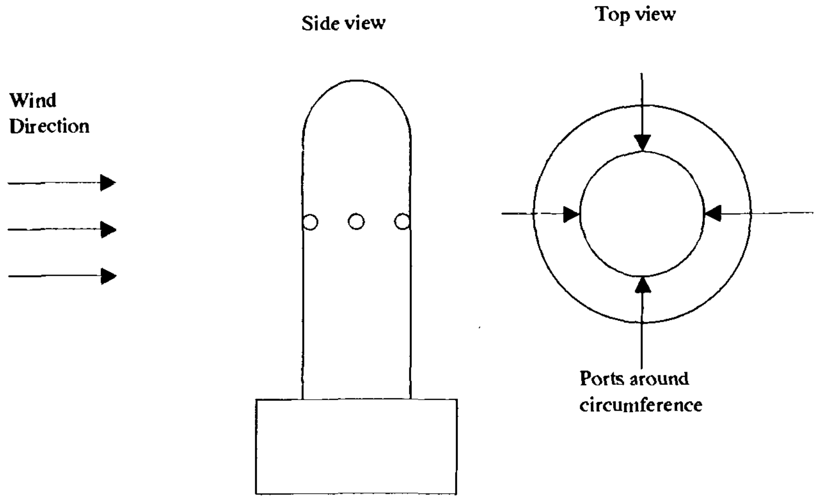
[5] Keran Claffey and Charles Reyerson. "Measuring Wind Speed in Freezing Rain." Focus 2000: Wind, Ice, and Fog, The Proceedings of the Fourth Annual Mount Washington Observatory Symposium. North Conway, NH: Mount Washington Observatory. (1994): 9-16.

measured parameter – force per area – is measured by a column of mercury exerting a known force per unit area.) The reason this measurement is primary is that the geometry of the propeller is such that in an ideal situation, as the air flows past the instrument, it is not disturbed at all by the vanes. This would be true only for vanes that are infinitely thin and air that is inviscid (zero viscosity.) Since neither of these conditions exists, the behavior of the helicoid anemometer will depart from this ideal. The R.M. Young anemometer is also unheated; this specific model is completely inappropriate for use on Mount Washington.

The second anemometer discussed is a Hydro-tech brand heated unit. It is a modified cup design; it will have the same basic properties of a standard 3 or 4 cup anemometer. This unit is capable of producing 1500 watts of heat that is cycled to control the temperature. Being a cup type design, it is subject to the same limitations as a standard cup anemometer. First among the concerns for this type of anemometer is the determination of each specific unit's factor, which is defined as the ratio of the true windspeed to the linear peripheral speed of the center of the cup. This factor must be determined experimentally, and thus the behavior of this type of unit cannot be described in terms of basic fluid mechanics. In addition, a cup anemometer is subject to variations in performance due to air density. A 30% reduction in static pressure (and hence density) can result in a reduction in indicated windspeed of 6%[6]. Not only does the anemometer need to be calibrated in terms of windspeed; its response to density variations must be determined as well. Thus the accuracy of this type of anemometer is a concern in high winds. Also, although the heaters in this unit may be adequate in freezing rain conditions, icing during Mount Washington winter conditions typically involve lower temperatures and much higher windspeeds. For these reasons this anemometer is not suitable for use at the Observatory.

The third anemometer tested is a Rosemount brand unit that operates on a similar principle to the pitot static anemometer. It consists of a heated cylinder with 8 ports around its diameter. Refer to Figure 1.2.

Figure 1.2 Rosemount Anemometer



Both direction and speed are calculated from two differential pressure sensors within the unit. The anemometer will have similar characteristics to a pitot tube combined with a

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[6] Bean, Howard S., ed., Fluid Meters. New York: ASME, 1971. p92.

reversed static tube. The disadvantage to this arrangement is that the differential pressure is dependent on the geometry of the ports in addition to the fluid properties. To give accurate measurements, this instrument must be calibrated over the full velocity range of interest and characterized for sensitivity to density variations. In MWO tests, accuracy was questionable at best. In addition, substantial icing was a continual problem in winter conditions.

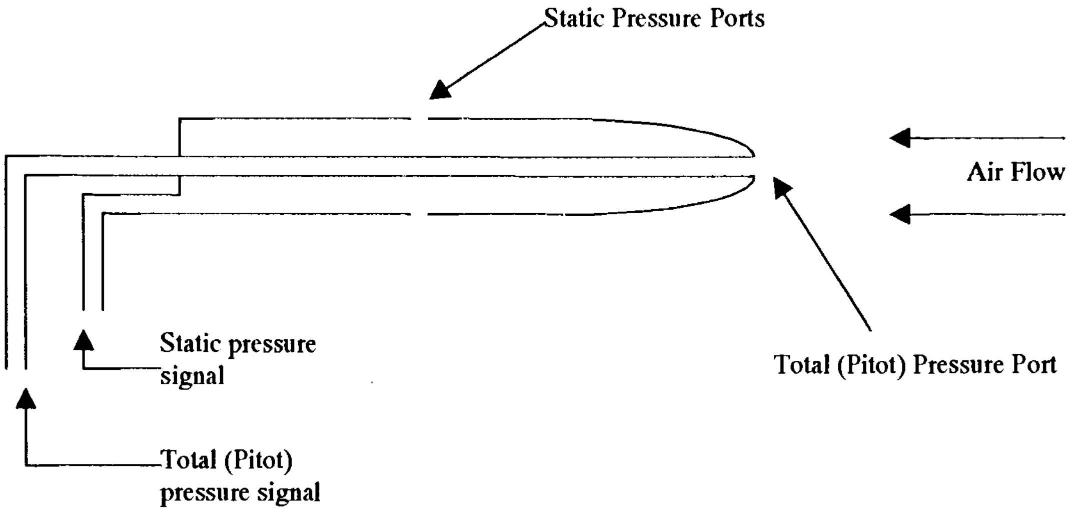
Ultrasonic anemometers are also worth mentioning. These anemometers typically have an array of acoustic transcievers that measure how long it takes a pulse of acoustic energy to travel from one location to another. By arranging the sensors appropriately, a two or three dimensional wind vector can be calculated. These anemometers have the advantage of high accuracy at low windspeeds and no moving parts. The main disadvantage is durability and vulnerability to icing. Several ultrasonic anemometers have been tested at MWO, with none proving to be durable enough to survive a typical winter. The most likely application for this type of anemometer is summer operation.

1.4 Justification for the Pitot Static Anemometer

The Pitot static anemometer at Mount Washington is a custom built device consisting of two main parts, a wind vane with a Pitot tube and an electronic instrumentation system. There are currently no commercially available Pitot static anemometers designed for meteorological use. One of the reasons for this is that Pitot tubes work best at high windspeeds, typically over 30 miles per hour. High winds are required to properly orient the wind vane to which the Pitot tube is mounted and the accuracy of the measurement greatly increases with an increase in windspeed (this effect will be explained in Chapter 3.) Low windspeeds are not a limitation on Mount Washington, except on calm summer days.

The Pitot tube is the sensing element and is a very simple device. It must perform two functions: it must have a port pointed into the flow such that fluid is brought to a halt right at the port's entrance. This is called the total pressure port or Pitot pressure port. It must also have a port (or multiple ports) pointed perpendicular to the flow that sense the static pressure of the air. These ports are precisely positioned to minimize errors due to turbulence as the air flows past the tube. See Figure 1.3. Experience has led to standardized geometries for Pitot tubes that meet these requirements to a very high degree of accuracy, even with small angular displacements such as those associated with meteorological measurements.

Figure 1.3 Pitot Tube Diagram



Discussions in engineering literature about the accuracy of Pitot tubes as a function of angular misalignment tend to be very general. "The actual size and shape of Pitot-static tubes vary considerably." And in a following paragraph: "In practice it is often difficult to align the Pitot-static tube directly into the flow direction. Typically, yaw angles up to 12° to 20° (depending on the particular probe design) give results that are less than 1% in error from the perfectly aligned results.[7]" This topic is also discussed in an American Society of Mechanical Engineers (ASME) publication which states "Velocity measurements – made with Pitot-static tubes similar in construction to those of figure 1.7.18 (which shows conical nosed and ellipsoidal Pitot tubes) – are correct to 0.3% if the angle between the mean stream path and axis of the impact tip is not greater than 12°[8]. Thus pitot tubes are not only tolerant of misalignment, they are extremely accurate. Although a Pitot tube is not easy to design or build, standard aircraft designs produce results that are sufficiently accurate for high-speed wind measurement on Mount Washington. In addition, they are very reasonably priced (less than 200 dollars.)

Recent technological advances that make a Pitot anemometer suitable for this application are the availability of relatively inexpensive and extremely accurate pressure sensors and the availability of inexpensive data storage. The combination of a good Pitot tube and a precision pressure sensor will be hard to beat for both accuracy and reliability.

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[7] Munson, Bruce and others. Fundamentals of Fluid Mechanics. New York: John Wiley & Sons, 1994. p119.

The Pitot tube serves another important purpose in the research at Mount Washington Observatory. For certain projects, Dr. John Lockwood of the University of New Hampshire's "Cosmo" project in particular, it is essential to know the true barometric pressure at the summit. The Cosmo project measures cosmic radiation at the observatory. The intensity of cosmic radiation is a function of the air mass over the detectors, which are on the Observatory's deck. Thus to compensate for the air mass over the detectors, the barometric pressure must be known as accurately as possible.[9]

At high windspeeds, the definition of barometric pressure becomes somewhat ambiguous. At Mount Washington, one of the reasons the winds tend to be high is the profile of the land. Refer to figure 1.4. The mountains and the layers of air overhead form a venturi. As air flows over the mountain, it is accelerated. The Bernoulli effect causes the faster moving air to have a lower pressure than air at the same altitude but away from the influence of the mountain.[10]

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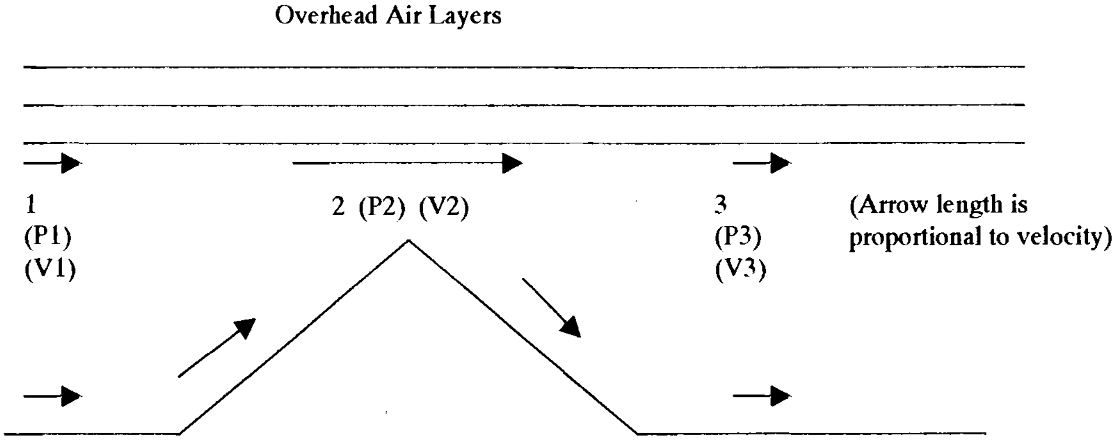
[8] Bean, Howard S., ed., Fluid Meters. New York: ASME, 1971. P102.

[9] Lockwood, J. A. "Variations in the Cosmic-Ray Nucleonic Intensity," The Physical Review Vol. 112, No.5 (1958): 1750-1758.

[10] Falconer, Raymond E. "Use of Pitot Tube to Compensate for Pressure Deficiency Caused by Wind on Mount Washington, New Hampshire," Transactions, American Geophysical Union Vol. 28, No. 2 (1947):

Figure 1.4 Mountain Effect on Barometric Pressure



The Bernoulli effect has serious consequences for the measurement of cosmic rays, since the intensity of cosmic radiation is a strong function of the total mass of air above the detector. This mass can be calculated easily from the barometric pressure when the air is still. However, when the mountain effect (also called the orographic effect) reduces the apparent barometric pressure, the calculated mass is also reduced.

R. Falconer's 1974 article[11] gices a detailed description of orographic measurement of barometric pressure and has served as a basis for the reasearch that has followed. Using the total pressure measured with a Pitot tube, one can compensate for the mountain effect. Refer to Figure 1.4. Air starts out at point 1 to the left of the mountain, at a pressure of P1 and a velocity of V1. As the air speeds up to V2 at point 2, its pressure is reduced to P2. If the air at point 2 is stopped at the tip of a Pitot tube, the pressure will increase to approximately P1, which is the total pressure of the air. Thus the calculated mass of the air column above point 2 will be more accurate, as the total pressure is a better representation of the barometric pressure that would be at point 2 if the air were still.

1.5 Thesis Organization

Chapter 2 provides an analysis of the system at the present time. It looks at both the hardware and at how windspeed is calculated. This step is necessary for correlation of historic data to data from the new design. Chapter 3 develops the formulas used to calculate windspeed and presents an analysis of the errors in the windspeed measurement. Chapter 4 describes the development of the hardware, software and networking that control the system. It includes a discussion of various computer control options and the selection for this system. Chapter 5 is a more detailed discussion of the software and operating system. Chapter 6 presents the results and conclusions.

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[11] ibid. 385-397.

Chapter 2

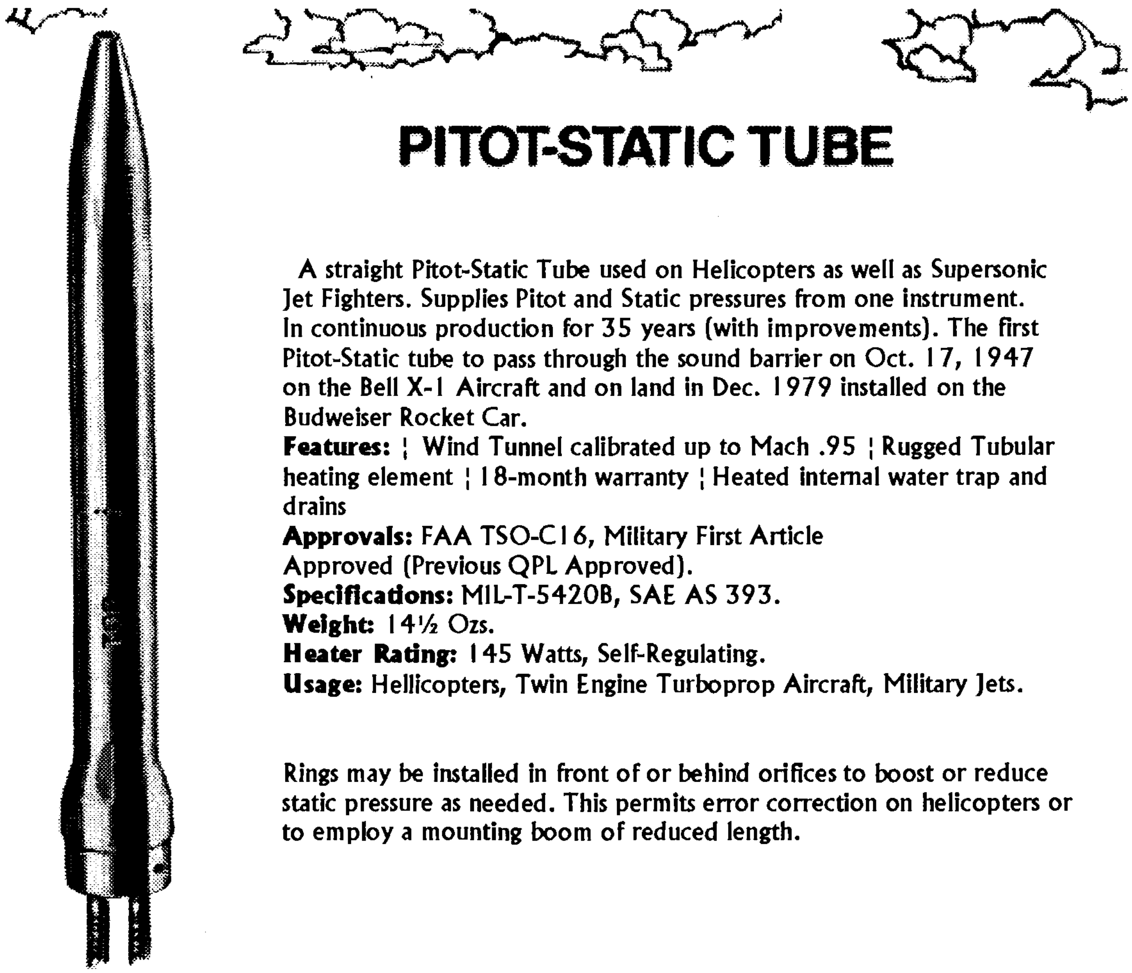
Pitot 92 Anemometer System

The purpose of this chapter is to analyze the performance of the pitot-static anemometer electronic instrumentation system in operation since 1992 at the Mount Washington Observatory, known as "Pitot 92." The main parts of this system are the Pitot tube / vane assembly, the Foxboro pressure sensor and the Campbell data logger.

2.1 System Description

The current Pitot static anemometer consists of a model AN5816-2 aircraft Pitot tube manufactured by Aero Instruments mounted on a wind vane on the observatory tower. Refer to Figure 2.1.

Figure 2.1 Aero Instrument Model AN5816-2 Pitot Tube[1]



PITOT-STATIC TUBE

A straight Pitot-Static Tube used on Helicopters as well as Supersonic Jet Fighters. Supplies Pitot and Static pressures from one instrument. In continuous production for 35 years (with improvements). The first Pitot-Static tube to pass through the sound barrier on Oct. 17, 1947 on the Bell X-1 Aircraft and on land in Dec. 1979 installed on the Budweiser Rocket Car.

Features: ¦ Wind Tunnel calibrated up to Mach .95 ¦ Rugged Tubular heating element ¦ 18-month warranty ¦ Heated internal water trap and drains

Approvals: FAA TSO-C16, Military First Article Approved (Previous QPL Approved).

Specifications: MIL-T-5420B, SAE AS 393.

Weight: 14½ Ozs.

Heater Rating: 145 Watts, Self-Regulating.

Usage: Hellicopters, Twin Engine Turboprop Aircraft, Military Jets.

Rings may be installed in front of or behind orifices to boost or reduce static pressure as needed. This permits error correction on helicopters or to employ a mounting boom of reduced length.

The output tubes are routed from the Observatory's tower to two manifolds behind the Observatory's Weather instrumentation wall via approximately 100 feet of ¼ inch Tygon brand plastic tubing and ¼ inch copper tubing. Several pressure measurement devices are connected to these manifolds. A standard U-tube manometer is connected as a primary standard, but it provides only a low-resolution visual measurement. A Hays brand circular chart recorder is connected to provide a continuous reading of the differential pressure at the pitot. This recorder is entirely mechanical and the calibration

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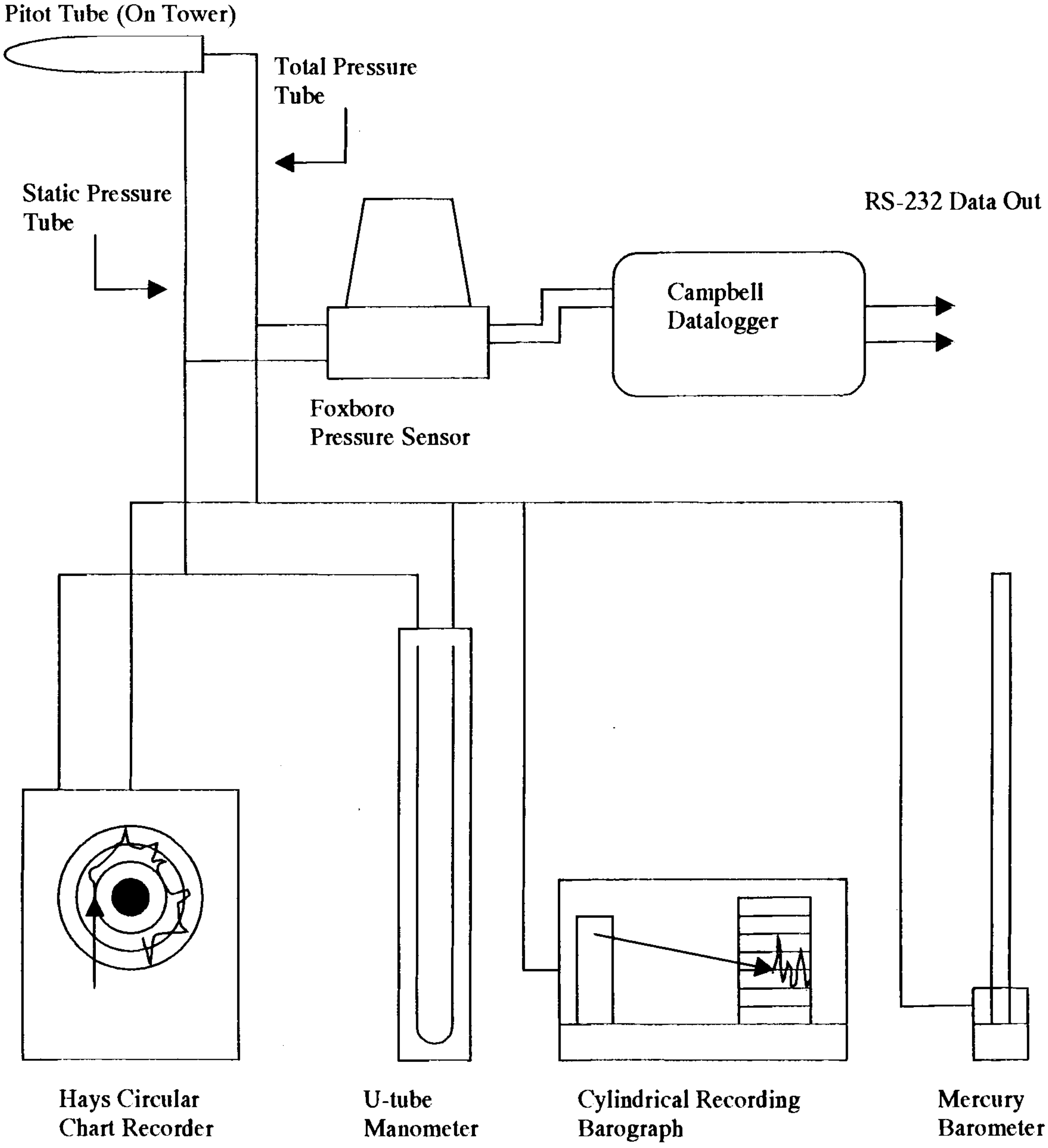
[1] Aero Instrument Company, Inc. Catalog. Cleaveland, OH. p6.

of the zero offset and the span are adjustable. The last device is a Foxboro differential pressure sensor, on which this analysis will focus. This transducer is of unknown age and calibration status. Figure 2.2 shows the major components of the system.

Figure 2.2 Pressure System Components



2.2 Signal and Data Path

As stated above, the windspeed measurement begins at the Pitot tube. The signal from the Pitot tube is a differential pressure which ranges from zero when there is no wind to approximately 20 inches of water at 200 mph. Note that this is a square relationship – the windspeed is proportional to the square root of the differential pressure. Thus a 100 mph wind will produce a differential pressure of 5 inches of water. This has several implications that will be discussed later in the error analysis but are worth mentioning here. The pressures in the system are very small; 20 inches of water is only 0.7 pounds per square inch. This means that the entire system must be kept free from leaks and protected from mechanical shock. Relatively small mechanical disturbances can easily produce pressures that will have a significant effect on the measured windspeed.

The tubing is one area where the Pitot-92 system as it stands is fairly well designed. The majority of the tubing from the Pitot tube to the weather wall is ¼ inch copper, which is heated and well anchored along the entire run from the tower to the weather wall. The main concern regarding the tubing is ensuring that all of the connections are sealed.

A factor that compromises the time response of the system is the enclosed volume at the instrument end of the tubing. In this installation, both the static and total pressure lines are attached to the Hays recorder, the manometer and the Foxboro. The total pressure is also connected to a mechanical barograph, and a mercury barometer. This extra volume has a damping effect that compromises the measurement. Although it is hard to put an actual number on how much damping is present, an estimate is developed in the error analysis presented in Chapter 3.

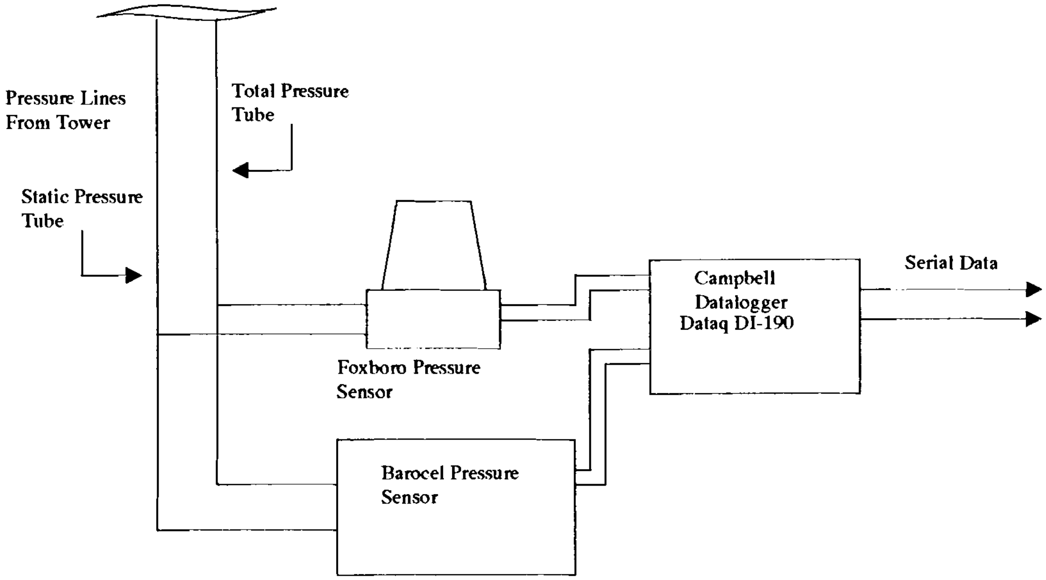
The windspeed measurement is calculated in two different ways from two of the above mentioned devices: the Hays chart recorder and the Foxboro pressure sensor. The Hays chart recorder reads directly in inches of water. A standard chart is used to calculate windspeed from the value recorded on the chart. Although this is not a very accurate measurement, it provides a useful estimate of the windspeed and a qualitative view of the variability of the wind. The more precise (but not necessarily more accurate) measurement is derived from the Foxboro. The remainder of this chapter will describe the calculation of the windspeed from the Foxboro sensor output and the associated errors.

2.3 Determining the Foxboro Output Voltage as a Function of Input Pressure

This section describes an in-circuit calibration performed in 1999 by the Robust Instrumentation Laboratory on the Foxboro pressure sensor, the first step in characterizing the system.

A pressure data acquisition system was installed at the Observatory on January 7, 1999. Refer to Figure 2.3. The system consisted of a two channel, 12 - bit Dataq voltmeter that was connected to both the Foxboro pressure sensor and a Barocel pressure sensor. The Barocel has full scale of 10 inches of water at an accuracy of 0.15% of full scale. This unit was used as the calibration standard. This system collected data once per second until January 30, 1999.

Figure 2.3 Test Setup: Foxboro Transducer Calibration



This experiment produced 86,400 (x2) data points per day, which is difficult to handle in a spreadsheet, so a QBasic program was used to sort through all of the data files and sample every 100th point. This sampling of 864 (x2) data points was used for the analysis. (A regression analysis is included in Appendix A.) The r^2 value for this data set is 0.99025, indicating a very linear relationship between the sensors, as expected. The key element of this analysis is the slope and intercept of the line. The Foxboro voltage is taken as the independent variable such that the resulting formula can be substituted into the algorithm used by the Campbell datalogger for further analysis.

Analysis of the Foxboro vs. Barocel data shows that the relationship between pressure input and voltage output is

$$P= .014713 *V -0.68525 \qquad (2.1)$$

where P is differential pressure (in inches of water) and V is the voltage (in mV) across the 10 ohm resistor across the output of the Foxboro.

Rearranging the equation to obtain voltage in millivolts as a function of pressure yields

$$V = 67.96 * P + 46.57 \qquad (2.2)$$

and finally dividing by 10.03 ohms (the measured shunt resistance) gives the transducer current output in miliamps as

$$I = 6.776 * P + 4.643. \qquad (2.3)$$

This relationship does not match any of the standard scale factor / offset options listed in Foxboro's documentation for this unit, thus data from this instrument is questionable. Since the transmitter is only designed to output 50 mA maximum, the highest pressure this transducer can measure is 6.69 inches of water, which corresponds to a windspeed of about 122 miles per hour. The electronics may saturate for larger values which means that the behavior of the transducer is unknown above this windspeed. Note that the jumpers that set the range on the Foxboro are set incorrectly; that is the jumpers do not match any of the three combinations listed in Foxboro's documentation. This would partially explain why the output range does not match any standard range, and calls into question all windspeed measurements above 122 miles per hour done with the Foxboro sensor.

2.4 Campbell Program Analysis

The voltage across the 10.03 ohm shunt resistor is connected to the Campbell datalogger's analog input 3. The datalogger runs the program shown in tables 2.1 to 2.3. (Each Campbell program has several "program tables" for different functions.) A “pseudo Basic” column is included to give a more intuitive sense to the Campbell machine code.

Table 2.1 - Campbell Datalogger Program Table 1[2]

	command	arguments	pseudo Basic
1	P 30	0.0, 6	F = 0
2	P 30	0.0, 7	G = 0
3	P 02	1, 5, 5, 13, 1.0, 0.0	D = CH5VIN * 1 + 0
4	P 37	13, 0.025, 13	M = M *0.025
5	P 17	3	C = PANELTEMP ‘thermocouple reference
6	P 14	1, 1, 4, 1, 3, 8, 1.8, 32	H = CH4TEMP * 1.8 + 32 ‘(Fahrenheit)
7	P 37	8, 108, 12	L = H * 108
8	P 21	1, 12	CH1VOUT = L ‘voltage to temp. indicators
9	P 87	0.0, 10	FOR COUNT = 1 TO 10 :PAUSE 0
10	P 02	1, 4, 3, 5, 0.5, 0.0	E = CH3VIN * 0.5 + 0 ‘xdcr voltage, +/-0.5V, 33uV res.
11	P 33	5, 7, 7	G = G + E
12	P 49	2, 5, 6	IF E > F THEN F = E
13	P 95		NEXT
14	P 37	7, 0.1, 7	G = G * 0.1
15	P 86	1	GOSUB WINDSPEED
16	P 31	7, 10	J = G
17	P 31	6, 7	G = F
18	P 86	1	GOSUB WINDSPEED
19	P 31	7, 11	K = G
20	P 37	10, 40, 14	N = J * 40
21	P 21	2, 14	CH2VOUT = N ‘voltage to windspeed indicators
22	P 92	0, 15, 10	IF REALTIME MOD 15 = 0 THEN FLAG0 = 1
23	P 77	110	(RECORD REALTIME)
24	P 71	1, 10	J = AVERAGE (J)
25	P 73	1, 10, 11	K = MAX (K)
26	P 00		END

---

[2] Ken Rancourt, MWO Campbell Datalogger Programming Procedure, 1992

Table 2.2 - Campbell Datalogger Program Table 2[3]

	command	arguments	pseudo basic
35	P 10	1	A = VBATTERY
36	P 17	3	C = PANELTEMP
37	P 14	1, 1, 1, 1, 3, 9, 1.8, 32.0	I = CH1TEMP ‘(Fahrenheit)
38	P 14	1, 1, 4, 1, 3, 8, 1.8, 32.0	H = CH4TEMP ‘(Fahrenheit)
39	P 37	3,1.8,4	D = C * 1.8
40	P 34	4,32.0,4	D = D + 32 ‘(PANELTEMP in Fahrenheit)
41	P 92	0,15,10	IF REALTIME MOD 15 = 0 THEN FLAG0 = 1
42	P 77	110	RECORD REALTIME
43	P 71	1,1	A = AVERAGE (A)
44	P 71	1,4	D = AVERAGE (D)
45	P 71	1,9	I = AVERAGE (I)
46	P 71	1,8	H = AVERAGE (H)
47	P 00		

Table 2.3 - Campbell Datalogger Program Table 3 - Subroutines[4]

	command	arguments	pseudo basic
27	P 85	01	SUBROUTINE WINDSPEED
28	P 34	7,-23.132,7	G = G - 23.132 ‘Subtract 46.57mV xdcr offset voltage
29	P 37	7,80.093,7	G = G * 80.093
30	P 34	7,0.27374,7	G = G + 0.27374
31	P 39	7,7	G = SQRT(G)
32	P 34	7,-4.6824,7	G = G - 4.6824
33	P 95		RETURN
34	P 00		

The program performs the following functions:

Table 2.1 (Program Table 1, *1 mode): Reads channel 4 thermocouple, scales the value and sends an analog signal out channel 1. It also reads the differential pressure signal at channel 3, computes the windspeed, checks to see if it is the maximum speed for the 15 minute interval and sends an analog windspeed signal out channel 2. Once per minute data is sent out the serial port. Once every 15 minutes the gust information is updated.

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[3] ibid.

Note: The purpose of the analog output signals is to drive three Electric Speed Indicator Company analog meters. In the summer, these meters are connected to a 3 cup anemometer.

Table 2.2 (Program Table 2, *2 mode): Reports the internal battery voltage and appears to have some redundant averaging operations.

Table 2.3 (Subroutine Table, *3 mode): Contains a windspeed calculation routine. The argument is the transducer output in millivolts divided by two, the output is windspeed in miles per hour.

On-line Data Transfer (*4 mode): The output from the Campbell is sent through the front panel serial port. The format is set in the *4 mode. In this program, parameter1 = 1 and parameter2 = 1, thus the output is tape disabled, printer enabled, ASCII, 1200 baud[5].

2.5 Algorithm Analysis

Analysis of the Campbell datalogger program reveals that the calculated windspeed as a function of voltage is

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[4] ibid.

[5] Campbell Scientific. 21X Micrologger Operator's Manual. Campbell Scientific, Inc. 1996. p4-2.

$$.V = \left\{ \sqrt{\left[\left[\left[(G * 0.5) - 23.132\right] * 80.093\right] + 0.27374\right]} \right\} - 4.6824 \tag{2.4}$$

where

G = averaged voltage from Campbell

V = wind velocity in miles per hour

which simplifies to

$$.V = \left\{ \sqrt{\frac{\left[(G * 0.5) - 23.132\right]}{.01248} + 0.2734} \right\} - 4.6824 \tag{2.5}$$

Note that the 0.5 scale factor appears in the "read voltage" command (line 10 of program table 1,) not in the windspeed subroutine. Substituting the voltage as a function of pressure for G yields

$$.V = \left\{ \sqrt{\frac{\left[((76.96P + 46.57) * 0.5) - 23.132\right]}{.01248} + 0.2734} \right\} - 4.6824 \tag{2.6}$$

Which simplifies to

$$.V = \left\{ \sqrt{\frac{2P}{.0006486} + 12.5234} \right\} - 4.6824 \tag{2.7}$$

This equation gives a "reasonable" number for indicated windspeed, which is quantified below. Equation 2.7 has the same basic form as the bernoulli windspeed equation that will be developed in chapter 3, however the offset and scale factors are undocumented and were in all likelihood empirically derived.

2.6 Quantitative Analysis

The greatest source of error in the current Pitot system is the formula used to compute windspeed, as it has no compensation for air density. Density is a function of temperature and barometric pressure. The formula used in the Campbell datalogger program assumes that the air is at 28F and 800 milibars (-2C and 80000 Pascals.) This will introduce unacceptable errors, as illustrated in Table 2.4, which shows the effect of varying the temperature across a typical range encountered on Mount Washington. The accuracy of the system in miles per hour is indicated in the difference column.

Table 2.4 Campbell Algorithm Examples

	Instrument Readings at 800 milibars, -22 deg. F			**Instrument Readings at 800 milibars, 68 deg. F**		
Differential Pressure (Inches of Water)	Bernoulli Windspeed (mph)	Campbell Indicated Windspeed (mph)	Difference (mph)	Bernoulli Windspeed (mph)	Campbell Indicated Windspeed (mph)	Difference (mph)
0.0	0.0	-1.1	-1.1	0	-1.1	-1.1
1.0	46.7	51.1	4.4	51.28	51.1	-0.2
2.0	66.1	74.1	8.1	72.52	74.1	1.6
4.0	93.4	106.7	13.3	102.56	106.7	4.1
6.0	114.4	131.7	17.3	125.62	131.7	6.1
8.0	132.1	152.8	20.7	145.05	152.8	7.7
10.1	147.7	171.4	23.7	162.17	171.4	9.2
12.1	161.8	188.2	26.4	177.65	188.2	10.5
14.1	174.7	203.6	28.9	191.88	203.6	11.7
16.1	186.8	218.0	31.2	205.13	218.0	12.9
18.1	198.1	231.5	33.3	217.57	231.5	13.9
20.1	208.9	244.3	35.4	229.34	244.3	14.9
22.1	219.1	256.4	37.4	240.54	256.4	15.9
24.1	228.8	268.0	39.2	251.23	268.0	16.8
26.1	238.1	279.1	41.0	261.49	279.1	17.7
28.1	247.1	289.9	42.7	271.36	289.9	18.5

Notice that the indicated windspeed is too high at both temperatures in this analysis. Also note that although this chart goes up to a differential pressures of 28 inches of water, the performance of the Foxboro sensor is unknown above 6.7 inches of water.

2.7 Conclusion and Recommendations

This system, although highly functional as a rough indicator of windspeed, has some serious deficiencies. Starting with the transducer and working down the line, they are as follows:

1) The range select jumpers on the Foxboro sensor do not match any of the arrangements documented in the instruction manual. Although it may be possible to calibrate the sensor using this arrangement, there is no evidence that this has ever been done. It is also impossible to tell what the output range is.

2) The current output from the transducer passes through a 10Ω resistor, which can transform a 4-50 mA signal into 0.04 - 0.5 volts. There is no other resistance in the loop; the Foxboro manual is very explicit about keeping the load resistance close to 600Ω. The very first step in "tuning up" the existing system would be to send the Foxboro in for calibration with a valid jumper setting. The Foxboro appears to have a more than adequate range (0 to 25 inches of water) and response time (on the order of that of the Barocel.) Therefore, this sensor would make an acceptable standard to measure differential pressure. Another drawback is the obsolescense of this sensor, which is no longer in production.

3) The Campbell datalogger program should also be updated. We have no way of knowing exactly why it is set up as it is, but at the time it was installed computers were much slower and memory was much more expensive. Thus it was probably a big advantage to have the Campbell relieve the computer of some of the work of averaging and data reduction. Unfortunately, much of the raw data is lost in this system and comparative studies with other modern systems are impossible. The datalogger should be retired from service and replaced with a PC based data acquisition system that stores raw data for subsequent analysis by researchers.

4) The need for each instrument should be assessed and the condition of the connections to the instruments checked. If possible, unnecessary equipment should not be attached to these manifolds. Reducing the number of instruments attached to the pressure manifolds and eliminating leaks will improve the time response and accuracy of the system.

This thesis addresses the first three concerns; the new instrumentation that is the result of this work makes the old instrumentation system obsolete. The fourth item is a matter of routine maintenance and assesing which instruments are necessary to provide useful weather data.

Chapter 3

Windspeed Measurement Design and Error Analysis

This chapter describes the computation required to calculate the windspeed from air properties as it relates to the new anemometer system design. Although this is a topic covered in all fluid mechanics texts, little attention is given to actual measurement techniques and error sources. In addition to a theoretical analysis of the errors, the last section of the chapter presents a practical analysis based on the actual instruments used in the new system.

3.1 Overview of Pressure Measurement in General

A common application for which Pitot-static systems are used for airspeed measurement is in aircraft. The Pitot-static tube is mounted on the nose or wing of the plane, where it is in the undisturbed "free stream" (air undisturbed by the body of the plane.) The function of the Pitot tube is to accurately convey the total (or Pitot) pressure and static pressure to two tubes, each of which is routed to different instruments. From these two pressures, four different measurements are produced: altitude, rate of rise, airspeed, and Mach number. Note that the airspeed using only a Pitot tube lacks compensation for temperature, and may not compensate for absolute pressure either. When temperature and barometric pressure are factored in, the measurement is called "true airspeed" which, despite its name, still contains errors. The measurement with which this thesis is concerned is true airspeed.

It is entirely possible to make a Pitot static anemometer using purely mechanical devices. Mechanical aircraft instruments that use mechanical bellows and complex geartrains to obtain measurements are common. Mechanical recorders have been in use at Mount Washington for decades, probably since the first Pitot tube was placed on the summit. This is inappropriate for a number of reasons. First of all, the windspeed data needs to be available for research purposes. Strip chart recorders may have been adequate in the past, but computer data is necessary now. Second, a precision mechanical device is subject to dirt and excessive drift over time and requires more maintenance than an electronic unit.

Other issues important for comparison studies are sampling interval and synchronization with a standard clock. For these reasons, an electronic system is the obvious choice for the MWO installation.

3.2 The New MWO Pressure System

The pressure measurement subsystem receives the static and total pressures from the Pitot tube and converts the pressures to voltage and serial data. In this design, the total pressure is measured using an electronic barometer manufactured by Paroscientific, Inc.[1] The difference between the total and static pressures is measured using a Model 239 differential pressure sensor manufactured by Setra Systems.[2]

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[1] Digiquartz Precision Pressure Instruments Programming and Operation Manual. Paroscientific, Inc. 1999.

[2] Setra model 239 High Accuracy / Low Pressure Range Transducer Datasheet. Accessed 15 April, 2001. Available from http://www.setra.com/tra/pro/p_te_239.htm

The Paroscientific barometer was chosen because it not only provides the absolute pressure necessary in the windspeed calculation, it is also accurate enough to serve as the station barometer. This is a proven unit that is exceptionally stable over time. It operates using a piezoelectric quartz crystal that oscillates at a known frequency. A bellows applies a pressure to the crystal proportional to the absolute pressure. This changes the frequency of the oscillations - the absolute pressure is then calculated from this change.

The Setra differential pressure sensor also has a number of exceptional features. The model 239 high accuracy / low-pressure transducer is accurate to 0.073% of full scale (optional - standard accuracy is 0.14%), and is temperature compensated from 0 to 175 degrees Celsius. Factory calibration is readily available, with a turn around time of 3 weeks.

3.3 Relationship Between Air Properties and Windspeed

The relationship between air properties and velocity are well known. In addition, the measurements attainable using relatively inexpensive equipment can follow theoretical values extremely closely.

Pitot tubes work on the Bernoulli principle, which is another way of writing the law of conservation of energy. According to this principle, in a moving fluid the sum of the static pressure, the kinetic energy per unit volume due to motion and the gravitational potential energy per unit volume is constant along a streamline.[3] This can be written as

$$p_1 + \frac{1}{2}\rho V_1^{\,2} + \gamma z_1 = p_2 + \frac{1}{2}\rho V_2^{\,2} + \gamma z_2 \tag{3.1}$$

where

p = static pressure,

ρ = density,

γ = specific gravity,

z = altitude, and

V = velocity.

It is important to note that this equation only holds when certain assumptions are made. The flow must be steady, inviscid and incompressible.[4] Although no physical system meets these requirements exactly, the first two assumptions hold for the analysis of this system. However, compressibility effects must be considered at the upper end of the wind velocity measurement range.

Refer to Figure 3.1. In equation 3.1, a 1 subscript indicates a point far in front of the Pitot tube. A 2 subscript indicates a point at the tip of the Pitot tube.

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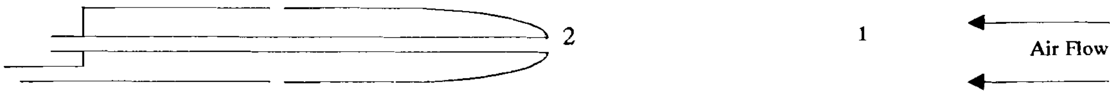
[3] Bruce Munson et al, Fundamentals of Fluid Mechanics (New York, John Wiley & Sons, 1994), 107
[4] ibid., 108.

Figure 3.1 Pitot Tube Mechanics



Since there is no significant change in altitude over the length of the Pitot tube, both γz are equal and can be eliminated. Since the air at the tip is not moving, the second (1/2 ρV^2) term goes to zero. Rearranging gives the basic Bernoulli velocity equation:

$$.V_1 = \sqrt{\frac{2(p_t - p_s)}{\rho_1}} \qquad (3.2)$$

Where

V_1 = Air Velocity (m/s),

p_s = Static Pressure (Pa),

p_t = Total Pressure (Pa), and

ρ_1 = Density of Air at Static Pressure (Kg/m^3.)

The density of air can be calculated directly from the ideal gas law:

Density = Pabs/(287*Tabs)

Where

Density is in Kg/m^3,

Pabs = absolute static pressure In Pascals, and

Tabs = absolute temperature in Kelvin.

Note: to convert from m/s to miles/hour multiply by 2.23694. (mile/hr = m/s * 2.23694)

The Bernoulli formula is adequate for windspeeds up to around mach 0.3 (0.3 times the speed of sound), above which the flow is no longer isentropic (i.e. not reversible) and other factors must be included. Mach 1 for an ideal gas is

$$c = \sqrt{RT\gamma} \qquad (3.3)$$

where

c = speed of sound,

R = Gas Constant (286.9 J/kg·K for air in SI units),

T = absolute temperature, Kelvin, and

γ = specific heat ratio (1.4 for air, dimensionless.)

Thus for air at 0°C:

$$c = \sqrt{286.9 * 273 * 1.4} = 336.8 m/s = 753 mi/hr \qquad (3.4)$$

Mach 0.3 at this temperature is 226 mi/hr – less than the world record. This indicates that compensation for compressibility is necessary. It turns out that if compressibility is not considered, the indicated windspeed will be about 16 mi/hr (6.4%) too high when the true windspeed is 250 mi/hr.

At higher gas velocities, the gas at the total pressure port on the Pitot tube undergoes an isentropic (i.e. reversible) compression. To account for this effect, the following relationship holds:

$$V = \sqrt{\frac{2\gamma}{\gamma - 1} * \frac{p_s}{\rho_t} \left[\frac{p_t}{p_s}^{\frac{\gamma-1}{\gamma}} - 1 \right]} \qquad (3.5)$$

Replacing γ with 1.4 and ρ with $(p_t - \Delta p) / (287 * T_{abs})$ yields

$$V = \sqrt{2009 * T * \left[\frac{p_t}{p_t - \Delta p}^{0.28571} - 1 \right]} \quad \text{(Units as listed above.)} \qquad (3.6)$$

This formula holds to Mach 1 and will be used in this system. (As stated previously, at higher velocities the isentropic compression assumption no longer holds and more factors must be considered.)

3.4 Error Analysis

The following sections detail the individual error sources in this system. Much of this information was derived from 99-00002-PRP: Performance Report: Pitot-Static Electronic Instrumentation as of 1-25-1999.[5]

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[5] Thoren, Mark, Performance Report: Pitot-Static Electronic Instrumentation as of 1-25-1999. Robust Instrumentation Laboratory at the University of Maine. Orono. 1999.

One fundamental problem with assessing the accuracy of this system is the fact that we simply do not have a way of calibrating the instrument the way we would prefer. The obvious best method would be to place the Pitot tube in a wind tunnel with a known air velocity, take a number of points, and place a number on the uncertainty. The problem is that air velocity is extremely difficult to measure. The standard technique in mechanical engineering laboratories is to use a Pitot tube and an electronic pressure sensor - exactly the instrument we are trying to calibrate! The problem then becomes how to place a bound on the error based on the accuracy of the individual instruments. For small errors in the input quantity, the error in the output can be expressed as follows:

$$u = \sqrt{\left(\frac{\partial y}{\partial x_1}\Delta x_1\right)^2 + \left(\frac{\partial y}{\partial x_2}\Delta x_2\right)^2 + \cdots + \left(\frac{\partial y}{\partial x_n}\Delta x_n\right)^2} \tag{3.7}$$

where

u = uncertainty,

x_i = input i,

Δx_i = error in input i, and

y = output.[6]

If y is a linear function of each x_i, this equation will hold for large errors as well.

Next, the partial derivatives of equation 3.6 are taken. The derivative of velocity with respect to differential pressure is

$$\frac{\partial V}{\partial \Delta p}\left(\sqrt{2009*T*\left[\left(\frac{p_t}{p_t-\Delta p}\right)^{0.28571}-1\right]}\right)=\frac{-\frac{2009*0.28571}{2}*T*\left(\frac{-p_t}{\Delta p-p_t}\right)^{0.28571}}{\left(\Delta p-p_t\right)\sqrt{2009*T*\left[\left(\frac{-p_t}{\Delta p-p_t}\right)^{0.28571}-1\right]}} \quad (3.8),$$

the derivative of velocity with respect to total pressure is

$$\frac{\partial V}{\partial p_t}\left(\sqrt{2009*T*\left[\left(\frac{p_t}{p_t-\Delta p}\right)^{0.28571}-1\right]}\right)=\frac{-\frac{2009*0.28571}{2}*T*\Delta p*\left(\frac{-p_t}{\Delta p-p_t}\right)^{0.28571}}{p_t\left(p_t-\Delta p\right)\sqrt{2009*T*\left[\left(\frac{-p_t}{\Delta p-p_t}\right)^{0.28571}-1\right]}} \quad (3.9),$$

and the derivative of velocity with respect to temperature is

$$\frac{\partial V}{\partial T}\left(\sqrt{2009*T*\left[\left(\frac{p_t}{p_t-\Delta p}\right)^{0.28571}-1\right]}\right)=\frac{\frac{2009}{2}\sqrt{\left[\left(\frac{-p_t}{\Delta p-p_t}\right)^{0.28571}\right]-1}}{\sqrt{2009*T*\left[\left(\frac{-p_t}{\Delta p-p_t}\right)^{0.28571}-1\right]}} \quad (3.10.)$$

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[6] Azar, Kaveh, ed. Thermal Measurements in Electronics Cooling. (Boca Raton: CRC Press, 1997), 67.

3.5 Interpretation

The relationships in equations 3.8, 3.9, and 3.10 show how the relative importance of each input quantity changes as the input quantities change. Inspection of equation 3.6 reveals that of temperature, differential pressure, and total pressure the windspeed measurement is most dependent on the differential pressure. Note that if the differential pressure is zero, then the windspeed is also zero. Equation 3.8 shows that as Δp increases, $\partial V/\partial \Delta p$ gets smaller. Thus at high windspeeds, the differential pressure sensor does not need to be as accurate for a given windspeed accuracy.

Equation 3.9 shows that with an increase in windspeed and hence Δp, the sensitivity of the windspeed measurement to p_t increases. Equation 3.10 shows that the sensitivity is not affected by variations in p_t or Δp, but it is inversely proportional to the square root of the absolute temperature.

3.6 Windspeed Error Due to Differential Pressure Uncertainty

Table 3.1 presents an analysis of two pressure sensor arrangements. The Bernoulli windspeed is calculated using a constant static air density of 1.039 Kg/m^3. The first arrangement uses two Paroscientific quartz resonator sensors, 0-15 psia (one for static pressure and one for total pressure). These sensors are rated at 0.01% F.S. accuracy. The second uses a single Setra model 239 which has a 25 inch of water full scale and 0.14% accuracy. This analysis assumes that the density error is zero in order to isolate the effects of uncertainty in the differential pressure.

The indicated windspeed is calculated for three conditions:

- assuming no error in differential pressure
- accounting for the error in two Paroscientific sensors
- accounting for the error in a single Setra 239 sensor.

The reason for this analysis is to compare two ways of measuring the differential pressure signal from the Pitot tube. The more common way of measuring differential pressure is to use a true differential pressure transducer. It is also possible to use two absolute pressure sensors and take the difference between the two readings, a technique used by DH Instruments with their Molbloc precision flow measurement system. This system is one of the finest available, with a specified accuracy of 0.2% of reading.

Table 3.1 Windspeed errors due to differential pressure uncertainty

True Pressure		Paroscientific 1016 B Errors					Setra 239 Errors				
			TRUE		TRUE	err band		TRUE		TRUE	err band
dp (Pa)	dp (in. water)	low	V (m/s)	high	V (mph)	(mph)	low	V (m/s)	high	V (mph)	(mph)
0	0.00	--	0.00	5.17	0.00	--	--	0.00	4.21	0.00	--
250	1.00	19.98	20.64	21.28	46.17	1.30	20.20	20.64	21.06	46.17	0.86
500	2.01	28.72	29.19	29.64	65.29	0.92	28.88	29.19	29.49	65.29	0.61
750	3.01	35.37	35.75	36.12	79.96	0.75	35.50	35.75	35.99	79.96	0.50
1000	4.02	40.95	41.28	41.60	92.33	0.65	41.06	41.28	41.49	92.33	0.43
1500	6.03	50.29	50.55	50.82	113.08	0.53	50.38	50.55	50.73	113.08	0.35
2000	8.04	58.14	58.37	58.60	130.58	0.46	58.22	58.37	58.52	130.58	0.30
2500	10.05	65.06	65.26	65.47	145.99	0.41	65.13	65.26	65.40	145.99	0.27
3000	12.06	71.31	71.49	71.68	159.92	0.37	71.37	71.49	71.62	159.92	0.25
3500	14.07	77.05	77.22	77.39	172.74	0.35	77.11	77.22	77.34	172.74	0.23
4000	16.07	82.39	82.55	82.71	184.66	0.32	82.44	82.55	82.66	184.66	0.21
4500	18.08	87.41	87.56	87.71	195.87	0.31	87.46	87.56	87.66	195.87	0.20
5000	20.09	92.15	92.30	92.44	206.46	0.29	92.20	92.30	92.39	206.46	0.19
5500	22.10	96.66	96.80	96.94	216.54	0.28	96.71	96.80	96.89	216.54	0.18
6000	24.11	100.97	101.11	101.24	226.17	0.26	101.02	101.11	101.19	226.17	0.18
6500	26.12	105.11	105.23	105.36	235.40	0.25	105.15	105.23	105.32	235.40	0.17
7000	28.13	109.08	109.21	109.33	244.29	0.24	109.13	109.21	109.29	244.29	0.16

Thus for any given windspeed, a single Setra differential pressure sensor performs slightly better than two Paroscientific transducers. Also note that the error due to pressure uncertainty becomes smaller as the windspeed increases. One argument for using a 0 - 30 inch of water Setra for measuring the differential pressure is that it is properly sized to use its entire measurement range for the range of windspeeds that the system must measure. The largest differential pressure that the system must measure is a small fraction of the range of the Paroscientific. Also, the time response of the Paroscientific is slow (on the order of 15 seconds.) This will compromise the ability of the anemometer to measure rapidly changing winds.

In conclusion, the Setra transducer is the appropriate choice for measuring differential pressure this application. In theory, it can provide an accuracy of +/- 1 mph at the low end of the scale and +/- 0.2 mph at the high end of the scale (250 mph.) In practice, there will be other errors associated with this measurement, including errors in the measurement of the transducer output voltage.

3.7 Windspeed Error Due to Density Uncertainty

Table 3.2 shows the effect of density uncertainty on the measured windspeed, taken around a true density of 1.17 Kg/m^3. Windspeeds are calculated in the same way as for Table 3.1, however the differential pressure is assumed to be 100% accurate for this analysis.

Table 3.2 Windspeed Errors Due to Density Uncertainty

dp (Pa)	dp (in. of water)	true speed	Windspeed error band (mph) for a given percentage density error				
		(MPH)	Paro 1016	Setra 270	Setra 276	(for ref.)	(for ref.)
			.01%error	.05% error	.25% error	1% error	2% error
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
250	1.00	46.17	0.00	0.02	0.12	0.46	0.92
500	2.01	65.29	0.01	0.03	0.16	0.65	1.31
750	3.01	79.96	0.01	0.04	0.20	0.80	1.60
1000	4.02	92.33	0.01	0.05	0.23	0.92	1.85
1250	5.02	103.23	0.01	0.05	0.26	1.03	2.07
1500	6.03	113.08	0.01	0.06	0.28	1.13	2.26
2000	8.04	130.58	0.01	0.07	0.33	1.31	2.61
2500	10.05	145.99	0.01	0.07	0.36	1.46	2.92
3000	12.06	159.92	0.02	0.08	0.40	1.60	3.20
3500	14.07	172.74	0.02	0.09	0.43	1.73	3.46
4000	16.07	184.66	0.02	0.09	0.46	1.85	3.69
4500	18.08	195.87	0.02	0.10	0.49	1.96	3.92
5000	20.09	206.46	0.02	0.10	0.52	2.06	4.13
5500	22.10	216.54	0.02	0.11	0.54	2.17	4.33
6000	24.11	226.17	0.02	0.11	0.57	2.26	4.52
6500	26.12	235.40	0.02	0.12	0.59	2.35	4.71
7000	28.13	244.29	0.02	0.12	0.61	2.44	4.89

For the absolute pressure measurement required to calculate density, the Paroscientific has a pressure error 1/5th that of the Setra Model 270. However, the 0.05% pressure error introduced by the Setra represents an error of only 0.12 mph at a true windspeed of 244.3 mph. Either sensor is adequate for this application, but the Paroscientific barometer is the NWS standard barometer[7] and would make an excellent addition to the Observatory's instrumentation.

All of the systems errors are summarized in Figure 3.2. This graph shows the worst case errors that can occur due to each instrument.

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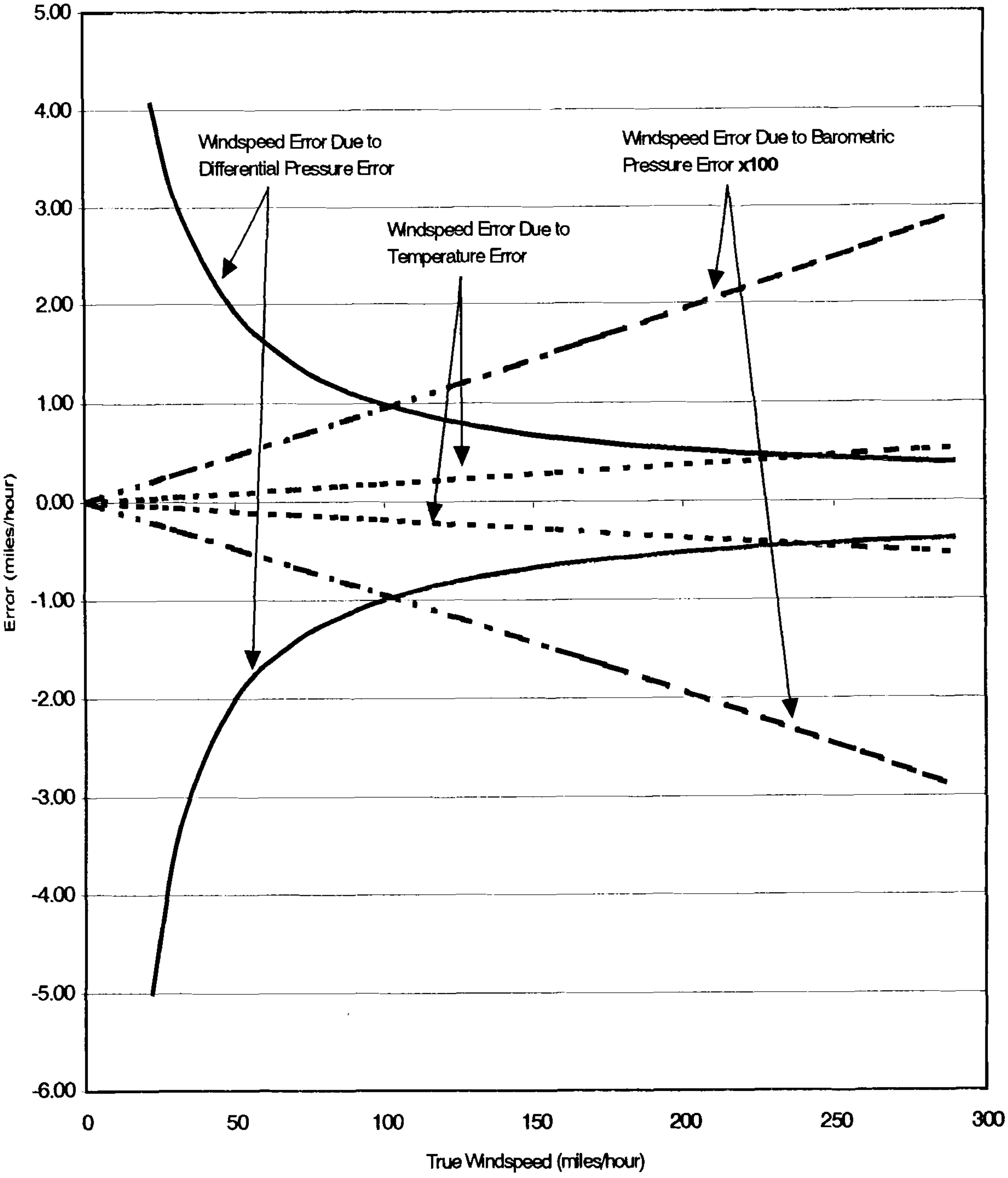
[7] John J Kelly, Jr. "Policy Statement on NWS Barometry" Operations Manual Letter. NWS, Silver Spring, 1998.

Figure 3.2 Pitot Instrumentation Errors at 800 kPa, 0 deg. C



3.8 Windspeed Error Due to System Lags

Another source of errors in a Pitot static system is the time for a pressure change at the Pitot tube to travel to the sensor. This error is made up of two components, acoustic lag and pressure lag.[8] Acoustic lag is due to the fact that no pressure change can travel faster than the speed of sound. This lag can only be reduced by reducing the tubing length, which may or may not be an option. The acoustic lag time is given by

$$\tau = \frac{l}{a} \tag{3.11}$$[9]

where

τ = acoustic lag time,

l = length of the tubing, and

a = speed of sound (approx. 330 m/s.)

For this installation the acoustic lag is

$$\tau = \frac{20}{330} = 0.06 \text{ seconds.} \tag{3.12}$$

The other error component is pressure lag. This lag is caused by viscous friction in the tubes connecting the Pitot tube to the instruments and the volume of the instruments.

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[8] William Gracey. Measurement of Aircraft Speed and Altitude. (Hampton, VA: NASA, 1980), 165

[9] ibid., 165

When the air velocity at the Pitot tube changes, the instantaneous pressure error due to pressure lag is

$$\Delta p = \lambda \frac{dp}{dt} \qquad (3.13)^{10}$$

where

$$\lambda = \frac{128\mu L V}{\pi d^4 p} \text{, the lag time constant of the system.} \qquad (3.14)^{11}$$

For equation 3.14,

μ = dynamic viscosity (1.488E-5 kg / (m*s) for air at 250K),

L = length of tubing (approx. 20 meters),

V = volume of system (estimate 10 liter, 0.01 m^3),

d = tubing diameter (0.00533m for ¼" copper pipe), and

p = absolute pressure (800,000 Pa on Mt. Washington.)

For this installation

$$\lambda = \frac{128 * 1.488 * 10^{-5} * 20 * 0.01}{\pi * 0.00533^4 * 80{,}000} = 1.87 \text{ seconds.} \qquad (3.15)$$

A useful exercise that also reduces the possibility for mistakes is to perform a dimensional analysis. Re-writing equation 3.15 with only the dimensions of each argument yields dimensions of $\lambda = \frac{kg}{m*s} * \frac{m}{1} * \frac{m^3}{1} * \frac{1}{m^4} * \frac{m^2 * s^2}{kg*m}$ = seconds, (3.16)

which is the correct dimensions of the output (seconds.)

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[10] ibid., 165

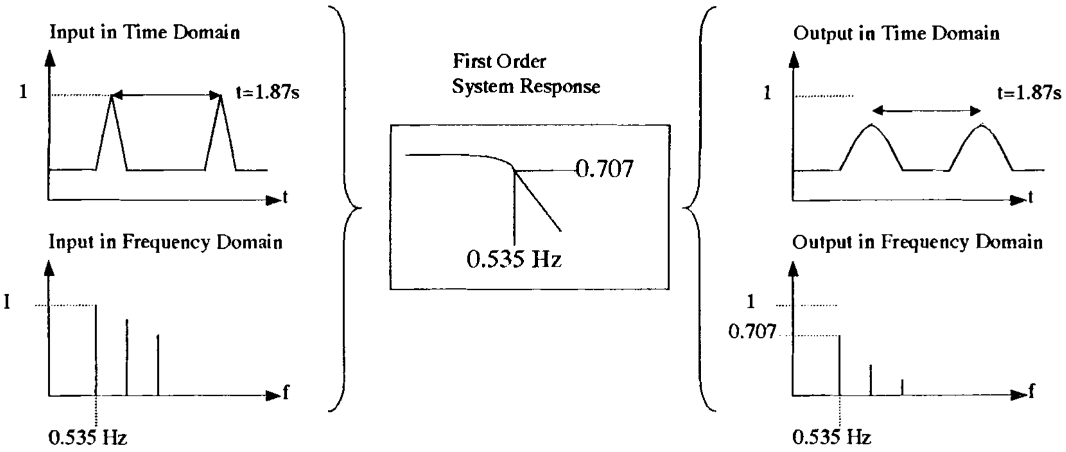
[11] ibid., 166

Another factor which was not considered in this analysis is the varying volume of certain instruments as the pressure varies. An example of this effect is the Hays chart recorder, that has a diaphragm that flexes under the force from the pressure signal.

This time lag of this system is acceptable when compared with the one second measurement interval. Sampling the windspeed once per second is roughly half the time constant of the system, thus sampling any faster is unnecessary. The reasonably low lag time of 1.87 seconds is due mostly to the ¼ inch tubing. Note that for tubing of half this diameter, the lag would be 30 seconds!

The significance of the instrument's time constant is that it puts a upper bound on the frequency of gusts that can be measured. If the time response of the system is assumed to be first order, the measured amplitude of gusts at the cutoff frerquency (1/1.87s = 0.535 Hz) will be reduced by a factor of $(0.5)^{1/2} = 0.707$. Non-sinusoidal gusts may be modeled as a sum of sinusoidal components. Figure 3.3 shows this graphically.

Figure 3.3 System Time Response Model



The end effect is to "smooth out" abrupt changes in windspeed. This effect cannot be avoided, as every instrument has a finite time response. It is, however, important to quantify the time response so that the limitations of the instrument can be realized.

3.9 Cost Analysis

This section is included to document the thought process that led to the selection of the pressure sensors. The decision was based on both economic and performance factors.

The following table shows the cost of the various configurations of pressure transducers that would work in the Mount Washington Observatory Pitot-static anemometer system.

- Configuration 1 (Not recommended): uses two Paroscientific 1016B sensors, one connected to the static pressure port and reconnected to the total pressure port.
- Configuration 2 (Recommended): uses a Paroscientific 1016B to measure static pressure and a Setra 239 to measure differential pressure between the static and total pressure ports.
- Configuration 3 (Recommended): uses a Setra 270 to measure static pressure and a Setra 239 to measure differential pressure between the static and total pressure ports.

In all three cases, the sensor connected to the total pressure port may be used as a barometer.

Table 3.3 Cost Analysis

Sensor	Paro 1016B	Paro 1016B	Setra 239	Setra 270	
Pressure Port connection	port 1 (static)	port 2 (total)	port 1 and 2 (differential)	port 1 (static)	Total Cost
Cost (each)	$4060	$4060	$730	$995	
Configuration 1	X	X			$8120.00
Configuration 2	X		X		$4790.00
Configuration 3			X	X	$1725.00

Configuration 2 was chosen because it provides the best performance in terms of measuring windspeed and includes the Paroscientific barometer, which will make the Observatory's barometric pressure measurements consistent with the NWS standard for barometers[12] and the World Meteorological Organization specification for a working standard barometer[13].

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[12] John J Kelly, Jr. "Policy Statement on NWS Barometry" Operations Manual Letter. NWS, Silver Spring, 1998.

[13] Guide to Meteorological Instruments and Methods of Observation, 6th ed. Geneva, Switzerland: World Meteorological Organization, 1996. pI.3-13.

Chapter 4

Data Subsystem Hardware Design

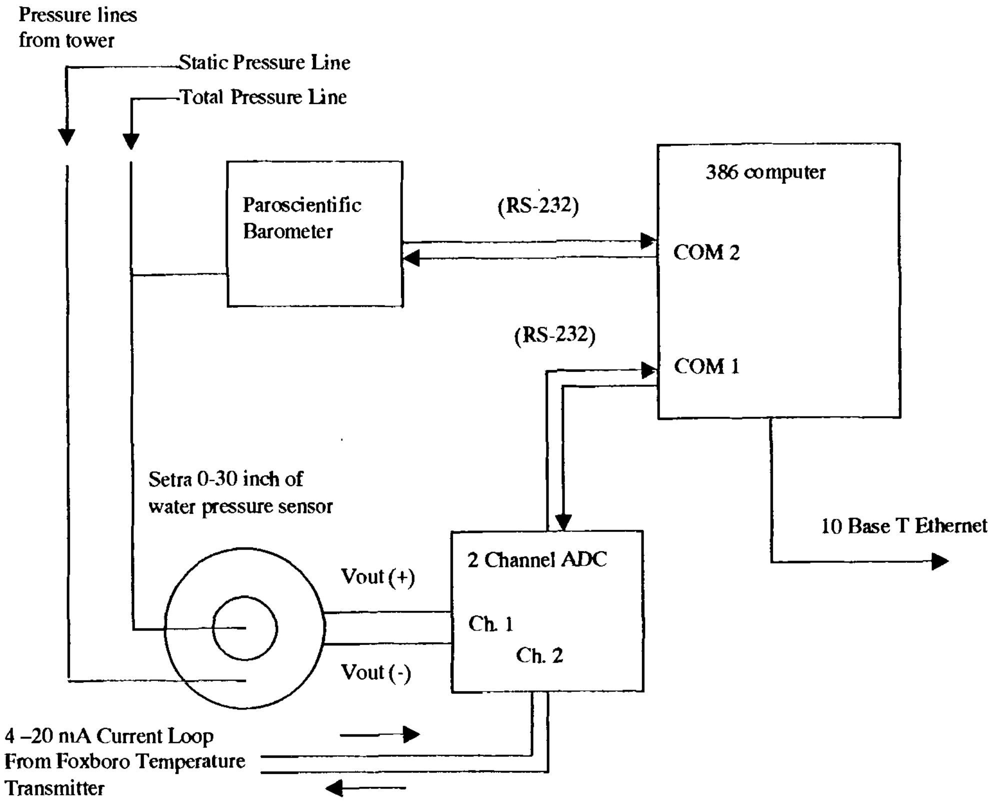
The data subsystem is the section of the Pitot static anemometer instrumentation system that receives the analog current signal from the temperature transmitter and the total and static pressure data from the pressure transducer outputs. It directly displays and stores the temperature and barometric pressure readings and uses this data to calculate the windspeed. The system is the Observatory's primary source of these measurements for observations and is responsible for reliably storing raw data in a convenient format for research purposes.

This chapter describes the design and construction of the system's hardware. It begins with an overview and then takes an in-depth look at the electrical requirements of each component.

4.1 Data System Hardware Overview

The data system consists of several parts, which will be detailed in the following sections. Figure 4.1 shows the relationship between the major components. The system measures three variables: temperature, total pressure, and the difference between the total and static pressure. Data is stored to another computer on the Observatory's network.

Figure 4.1: Data System Hardware



4.2 Paroscientific Barometer

A Paroscientific Model 1016B barometer measures the total pressure. In this application, it is configured to send a pressure reading approximately every 15 seconds at 9600 Baud, 8 data bits, no parity, 1 stop bit. The data is framed as follows:

*0123.456*0123.456*0123.456*0123.456 etc.

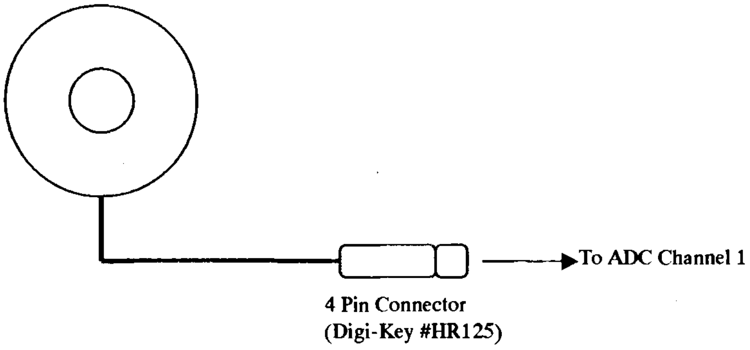
where the asterisk preceeds the data for each transmission, followed by the data in the units specified in the barometer setup. In this application, the units are kiloPascals.

The fact that this instrument has direct digital output makes it the simplest in terms of its electronic interface. The other instruments require more care.

4.3 Setra Model 239

The Setra Model 239 low differential pressure transducer measures the difference between the total and static pressure. The transducer is powered by +12V and –12V from the main power supply through the connection to the ADC. The output from the transducer is 0 to 5 volts differential. The output has a significant common mode voltage (5 – 7 volts) that must be accounted for in the data acquisition system. The transducer must be operated as a four terminal network; meaning the signal ground must float with respect to power ground.

Figure 4.2 Setra Transducer Electrical Connections



Pin Connections

White to Pin 2 (+12 V)

Black to Pin 3 (-12 V)

Yellow to Pin 1 (+ Output)

Brown to Pin 4 (- Output)

Shield connected to metal connector housing, all other wires separately insulated.

4.4 Custom-Built Analog to Digital Converter (ADC)

There are many ways of attaining an accurate voltage measurement from the differential pressure transducer. A Dataq DI-190 2 channel, 12 bit analog module has routinely been used for reasonably accurate measurements around the lab. Several companies make cards that plug into an ISA slot on a PC motherboard. After researching several of these devices, a custom built analog data acquisition circuit that has exactly the features that this system requires was developed. Although this may sound like a rather difficult task at first, careful selection of components allows an extremely simple design.

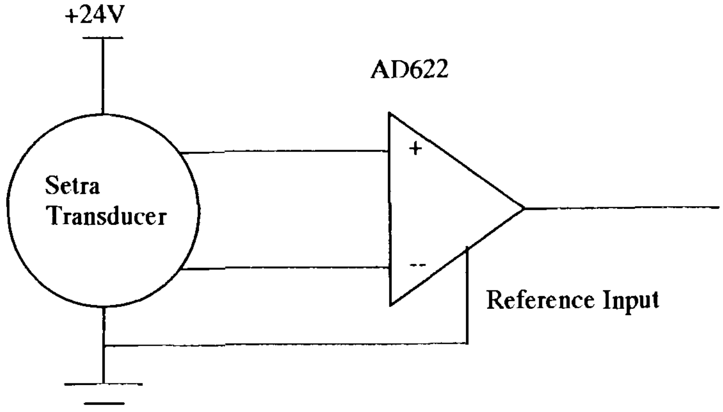
4.4.1 Preliminary Information

The first inspiration for the circuit was an advertisement for the Linear Technology LT2400 24 bit ADC. This unit has resolution greater than 1 ppm and accuracy better than 4 ppm. For comparison, a 4000 count digital voltmeter has a resolution of 250 ppm. The package is an SO-8 IC and the data output is via a 3-wire serial interface. Linear Technology provided an evaluation board, which was very impressive.

The next step was to construct an adapter cable to connect the LTC2400 evaluation board to a Parallax Basic Stamp 2 (BS2). A BSII program tells the ADC to run a conversion, shift all 32 bits of the output word into two 16 bit variables, then send the result out the serial port as 8 hexadecimal characters. This worked very well with a minimum of troubleshooting.

The input to the LTC2400 can accept a 0 to 5 volt signal directly. However, as stated previously the Setra output is not referenced to ground. To account for the common mode voltage of the Setra, a unity gain differential input instrumentation amplifier references the signal to ground as shown in Figure 4.3.

Figure 4.3 Setra Interface

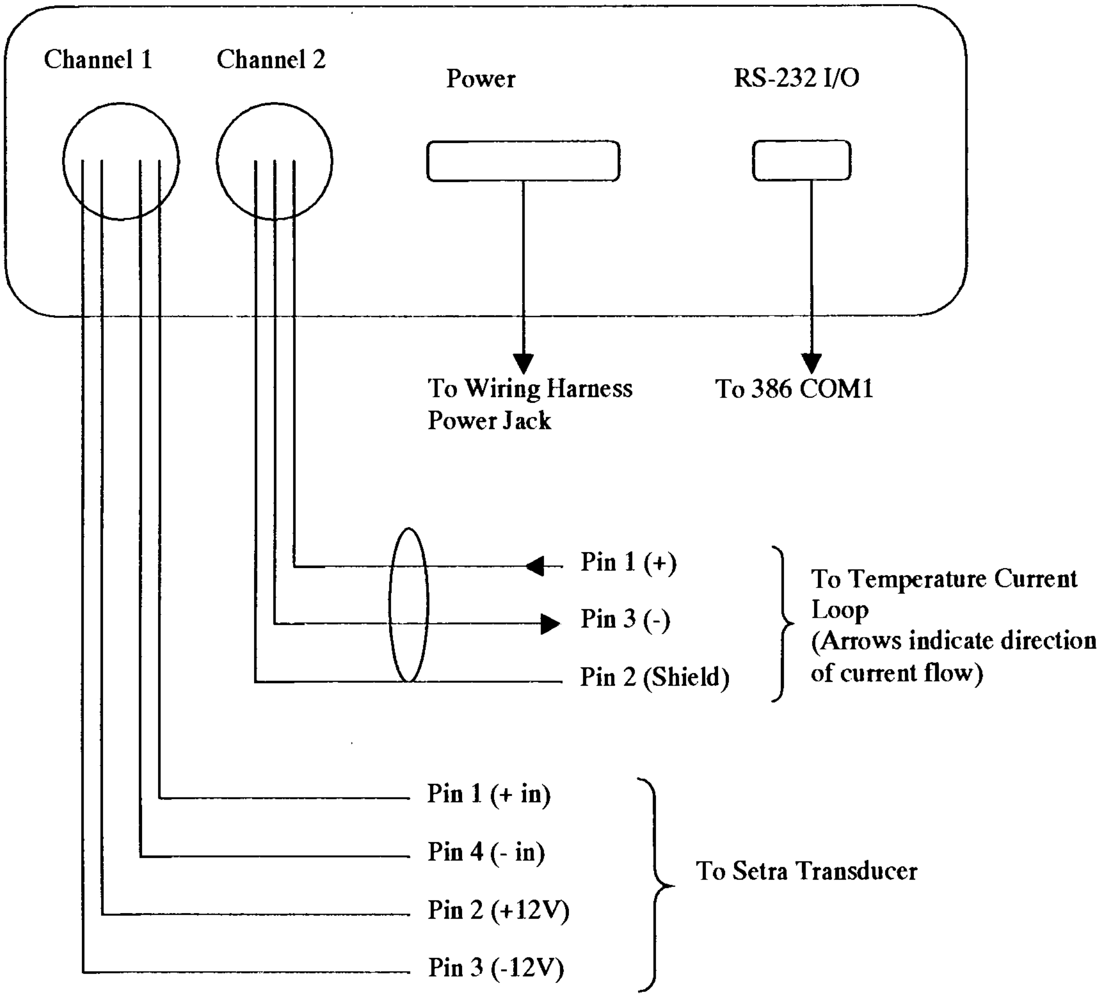


4.4.2 Circuit Construction

A two channel ADC based on the LTC2400 was then constructed for the anemometer. The input stage consists of a unity gain differential amplifier as a buffer. The amplifiers are AD622 B-grade units, that allow differential mode inputs with a common mode range from -10 to +10V, referenced to system ground. (This is adequate for the Setra pressure transducer, which has a common mode voltage 5 to 7 volts above the negative supply voltage.)

The ADC subcircuits follow the evaluation board circuit closely. The voltage reference is an LT1236 A-grade, .05% accurate, 5 ppm/C max temp coefficient unit. There is a provision to measure the temperature of the ADC itself with a Dallas Semmiconductor DS1620 solid state digital temperature sensor. All operations are coordinated by the BS2 microcontroller. The BS2 has several commands for interfacing to "3-wire" serial devices and RS-232 devices. It is an excellent choice for this application as the LTC2400 and DS1620 use 3-wire interfaces and the system is interfaced to the outside world via RS-232. A programming connector inside the system box was provided for changing the BS2 software. The main communication takes place at Basic Stamp ports P0 and P1 (transmit and receive, respectively). These pins are connected to a MAX232 level converter to allow direct connection to an RS232 device. The complete schematic for the ADC is included in the appendix.

Figure 4.4 ADC Box Connections



4.4.3 ADC Serial Protocol

The serial protocol is similar to that of the Paroscientific barometer. A command is sent to the device, which then responds after performing the requested task. For this system, the commands are sent to the RS232 port at 9600 Baud, 8 data bits, no parity, 1 stop bit. The reply is sent out the same port in hex format as ASCII characters, MSB first, terminated by a carriage return (ASCII 13.)

Table 4.1 ADC Commands and Responses

Command	Action	Output Format
1	Read CH1 Voltage	Nibble 7 .. Nibble 0, carriage return
2	Read CH2 Voltage	Nibble 7 .. Nibble 0, carriage return

The procedure for converting the hexadecimal output to a voltage is as follows:

A = A – 0x20000000 (Subtract 2^{29} offset)

A = (float)A / 268435456.0 (divide by maximum count to get fraction of full scale)

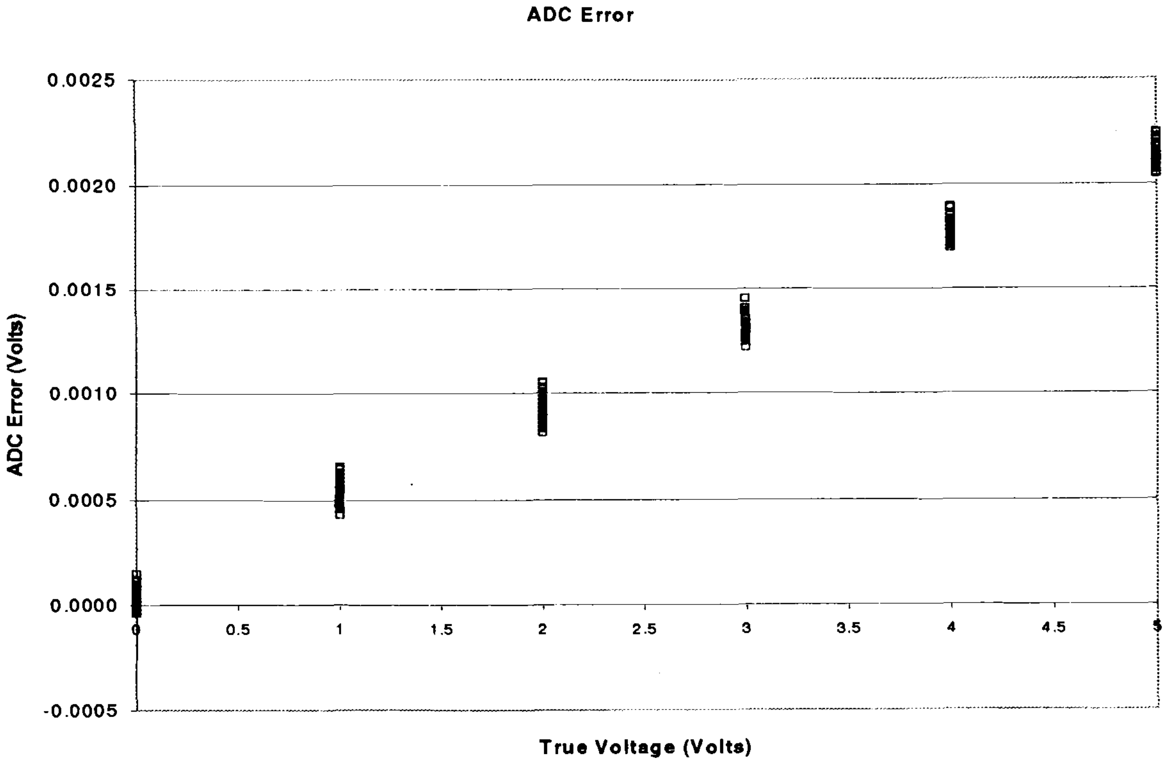
A = A * 5.0 (Multiply by full scale voltage)

4.4.4 Error Measurement

The ADC was calibrated on May 13, 1999 using a Keithley 196 six digit voltmeter and a precision adjustable voltage source. Data was gathered using a Basic program that generated a spreadsheet file. Test points were approximately 0, 1, 2, 3, 4, and 5 volts. Fifty data points were taken for each voltage and analyzed. The results show that the absolute accuracy is better than 0.04%. For any one voltage, the maximum spread for the 50 data points was 239 microvolts (Channel 2, 2 volt input.) This is equivalent to a resolution of 1 part in 20900, or 14.3 bits.

A conservative number for the accuracy of this unit is 0.045%.

Figure 4.5 ADC Error



4.5 Computer Hardware Selection

Many different programable controllers would work for this installation. At the low end of the spectrum, each device could be connected to any one of the Observatory's computers through a serial interface with no other controller. This has the advantage of not adding another computer to the network, and it would keep the anemometer simple.

A microcontroller could be used for timing and calculation of windspeed, but it would need three serial ports and still would require synchronization to a master clock. Similarly, PLCs are available with ethernet ports. The present setup uses a Campbell datalogger, that has all of the timing and calculation functions built-in.

A desktop PC is almost perfect for this application. It is easy to add serial ports, it is easily programmable, and it is easy to network. The drawbacks are that it is not as robust as an industrial controller and it has all of the problems associated with RAM and hard drives (volatility of RAM and hard drive mechanical failure.) However, the positive aspects of a PC justified its use. Instead of a desktop PC, this system uses an industial embedded PC.

PC-104 refers to a standard for industrial PCs. It uses the standard 16 bit ISA bus with a different connector, and the footprint is smaller and stackable with the associated add-on cards. A typical industrial PC-104 system consists of a motherboard and several stackable modules, including digital I/O, analog I/O, video, etc. As far as software and operating system are concerned, it is just a standard PC.

The heart of the this data system hardware is an Acrosser AR-B9606 industrial grade 386 computer. This board was chosen because it is small and it has built in Ethernet, 4 serial ports, floppy drive controller, and hard drive controller. The calculations that the computer must perform are fairly simple, making a 386-40 MHz more than adequate for this application. The necessary connections to the computer board are as follows:

Table 4.2 Computer Connections

Board Connector	**Function**	**Connects To**
CN4	IDE interface	Hard drive
J3	Power Connector	+5v, GND
DB2	COM1	ADC box
DB1	COM2	Paro barometer
CN1, CN2	PC-104 Bus	PC-104 to ISA board
CN3	Keyboard port	Keyboard
CN7	RJ-45 Network port	Network

As delivered, a generic VGA card was installed in the PC-104 to ISA converter board. Any ISA video card should work, including a CGA card with composite video out. A CGA card will allow any standard NTSC monitor to be used as a display. The connections to the computer shown in Table 4.4 may be omitted for operation but are useful for setup.

Table 4.3 Optional Computer Connections

Board Connector	**Function**	**Connects To**
CN5	Floppy controller	Floppy drive
CN6	Parallel Port	Data transfer cable

There is nothing special about this computer – it is a slow 386, identical in architecture to old 386 desktop systems. The major differences are in size, degree of integration and durability. For maintenance purposes, this machine is just another PC. The computer software is detailed in Chapter 5.

4.6 Wiring Harness

All power is distributed via the main wiring harness. Power enters the harness through 4 ring lugs and is routed to 2 D-Sub 15 female connectors, a male D-Sub 9 connector and a female D-Sub 9 connector wired as follows:

Table 4.4 Wiring Harness Connections

D-Sub(x) Connector	**Ground**	**+5 Volts**	**+12 Volts**	**-12 Volts**	**Barometer Transmit**	**Barometer Receive**
X1	5				2	3
X2	5		9		2	3
X3	1,2,3,9,10	4,5,11,12	6,13,14	7,8,15		
X4	1,2,3,9,10	4,5,11,12	6,13,14	7,8,15		

A schematic of the wiring harness is shown in the appendix.

The hardware underwent extensive testing in the summer of 1999 with preliminary test software. It proved to be a reliable foundation for the system and allowed software to be developed without concern of hardware related problems.

Chapter 5

Development of Software and Computer Display

This chapter describes the design process for the computer control portion of the Pitot anemometer data system. Chapter 4 described the various hardware connections to the computer; the operating system and software will now be examined. This chapter also describes the operation of the display running on the Observatory's "Weather Wall," i.e., the wall where all the weather instruments are centralized.

5.1 Operating System Selection

After choosing the computer hardware, the next decision to be made was the operating system it will run. The choices for this installation are DOS, Windows or Linux. The first OS may seem surprising, as it has been all but eliminated from modern desktop PCs. However, it has the advantage of low memory usage, it will run on an 8088 based embedded PC, it is easy to program, and it can run a single program very reliably. It is still quite common in industrial computers. The major drawback is with networking. The various network tools available for DOS are rudimentary at best. This is mainly a function of DOS's single-tasking nature; it cannot coordinate the many programs that use the network interface. Some exceptions to this rule are true multitasking DOS operating systems, such as DR-DOS and JK Microsystems eRTOS (embedded real-time operating system.) An attempt was made to install DR-DOS, however it proved as cumbersome as MS-DOS in terms of networking. JK Micro's software is prohibitively expensive and is designed for use on their hardware only.

A Windows based system would work, but it is overkill for this application and is prone to crashing. In addition, the operating system overhead would represent most of the computer's load. Thus the computer would need to be much more powerful than necessary for the actual work it must perform.

DOS was chosen for the initial installation because of its simplicity and very low overhead. The basic network support is adequate for this system, as the only function required is network drive mapping. Another important advantage is that most people understand DOS and BASIC, the language in which the main program was written.

Linux presents a potentially superior platform for this application. Although the major Linux distributions require large amounts of RAM and hard drive space (32 Megabytes / 500 Megabytes, respectively), there are also many distributions that are intended for low memory and/or embedded use. One distribution that would be suitable for this application is MuLinux from Italy[1]. It is attractive because it has full network support, it will run on an 80386 with 16 Megs of RAM, and it is easy to configure.

5.2 Data System Software

The software running on the 386 computer performs all of the basic functions required to acquire data, calculate the necessary weather parameters and store the data in a logical format. The program is written in Basic and was compiled using MS QuickBasic, but it may be compiled using any suitable compiler.

The design specifications for development of this program are as follows:

- Data must be written to an archive machine on the observatory network automatically, not requiring the assistance of any other machine.
- The software must be able to run disconnected from the network, storing data locally until it may be copied over the network to the archive.
- The windspeed will be recorded once per second. Other parameters will be stored once per minute.

The system is designed to operate continuously once started. The program uses several files to control its operation. The main program (PITOT.EXE) resides in C:\PITOT. A parameter file must reside in the same directory as the executable (PARAMS.TXT.) This file contains text strings indicating where to put the output files, the display file and calculation adjustment factors. An example PARAMS.TXT file is shown in Figure 5.2.

On boot up, the datasystem computer's AUTOEXEC.BAT file maps the remote computer's data storage directory as its F:\ drive (As delivered, it is the C:\DATA directory on the remote computer). The first line of the PARAMS.TXT configuration file tells the program to store data to this directory.

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[1] "MuLinux Project Homepage," accessed 22 April, 2001; available from http://mulinux.nevalabs.org/

5.3 Network Setup and File Structure

The 386 computer is connected to the MWO computer network. It is running MS DOS version 6.22 and MS Lanman version 2.2c. The directory structure on the local hard drive is

```
C:
        \DOS
        \LANMAN.INS
        \LANMAN.DOS
        \PITOT
        \DATA
```

The functions of the directories are

DOS: Contains all system files for MS DOS version 6.22.

LANMAN.INS: Contains the installation files for MS Lanman version 2.2c.

LANMAN.DOS: Contains the program files for MS Lanman version 2.2c.

PITOT: Contains the program executable and parameter file.

DATA: redundant data storage

Drives on this machine are as follows:

A:\ First floppy (not normally installed)

B:\ Second floppy (not normally installed)

C:\ Local hard drive

D:\ Interlink drive - floppy on host machine

E:\ Interlink drive - hard drive on host machine

F:\ Network drive - main data storage directory on the network.

Drives D and E are optional interlink drives that may come in useful for setting up a machine for the first time. The DOS interlink help file has detailed information on this program. The files that the data system computer accesses over the network reside in the same directory, to minimize complexity and reduce the possibility of failure.

5.4 Software Operation

This section discusses the operation of the software. The source code listing is included in the appendix. The computer's functions are as follows:

- Read both ADC channels and convert to volts
- Convert voltages to temperature and differential pressure
- Respond to output from the Paroscientific barometer
- Calculate windspeed
- Append data to the appropriate hourly file
- Over-write current data to small file containing display information

The Basic program running on the 386 performs all necessary calculations on the raw data. This includes getting absolute pressure readings from the Paroscientific barometer and getting the raw voltages from the ADC. The program flow is best understood by examining the main program loop and each subroutine:

Figure 5.1 Main Program Loop

```
MAIN:
 INITIALIZE
 GETPARAMS
 NEWHOUR
 NEWBACKUP

 DO
    STARTTIME = INT(TIMER)

    SELECT CASE UCASE$(INKEY$)
            CASE "Q"
               GOTO QUIT
            CASE "N"
               NETGOOD = 1: NEWHOUR
            CASE "L"
               NETGOOD = 0: CLOSE #3
            CASE "B"
               MAKEBACKUPS
    END SELECT

    IF INT(VAL(MID$(TIME$, 1, 2))) <> REMEMBERHOUR THEN  'DETECT NEW
HOUR
        CLOSE #4: NEWBACKUP
        IF NETGOOD = 1 THEN
           CLOSE #3: NEWHOUR
        END IF
     END IF

    GETVOLTS
    GETTEMP  'REM THIS LINE FOR TEST WITHOUT FOX. TEMP SENSOR
'   TEMP = 0 'UN-REM THIS LINE FOR TEST
    GETWSPEED
    GETAVG
    WRITELOCAL
    IF NETGOOD = 1 THEN WRITEDATA
    WRITEBACKUP
    DO WHILE INT(TIMER) = STARTTIME: LOOP
 LOOP

STOP
END
```

INITIALIZE:

This subroutine tells the barometer to send continuous readings to COM2, tells the computer to respond to data from the barometer, and initializes some global flags.

GETPARAMS:

This subroutine opens and reads the operating parameters from THE “PARAMS.TXT” parameter file. In order, the parameters are network path for data, machine to synchronize clock with, channel 1 zero offset, channel 1 span multiplier, channel 2 zero offset, and channel 2 span multiplier.

Figure 5.2 Example PARAMS.TXT File

```
F:\DATA\
OBSERVER_1
-0.0182
0
0
0


'THIS IS THE PITOT-STATIC ANEMOMETER PARAMETER FILE.
'IT CONTAINS THE FOLLOWING INFORMATION, IN THIS ORDER:

'PATH TO DIRECTORY WHERE DATA IS STORED
‘NAME OF COMPUTER OT SYNCHRONIZE CLOCK WITH
'CHANNEL 1 ZERO ADJUST
'CHANNEL 1 SPAN ADJUST
'CHANNEL 2 ZERO ADJUST
'CHANNEL 2 SPAN ADJUST
```

NEWHOUR:

Creates a new output file. It checks the size of the file to determine if it has been created before. If it is smaller than 10 bytes, then header information is written to it. (The header information takes up more than 10 bytes.)

NEWBACKUP:

Opens the appropriate local backup file on the hard drive. There are 24 local backup files, one per hour, that get overwritten continually.

"MAIN" Program Loop:

The main loop is a DO loop that is executed once per second. At the beginning of the loop, variable "starttime" is set to the system clock. After the execution of the loop, the program waits in a DO WHILE loop until the next second begins.

The MAIN loop scans the keyboard to check if the operator has entered a command. Next, it checks to see if it is time to make a new hourly file and write to the next local backup file. The rest of the main loop is segmented into subroutines, described separately below.

GETVOLTS:

This subroutine sends commands to the analog to digital converter and reads back the voltages from both channel 1 (differential pressure sensor) and channel 2 (temperature sensor.)

GETTEMP:

Converts the voltage from channel 2 to temperature.

GETWSPEED:

Converts temperature, pressure and channel 1 voltage to windspeed. First, it converts ch.1 voltage to differential pressure. Next, it converts temperature and barometric pressure to density. The windspeed in miles per hour is then calculated from the density and differential pressure.

GETAVG:

Once per second, this subroutine computes the average windspeed for the last 5 seconds. Also computes the average for the last 10 minutes and keeps track of the maximum and minimum windspeeds for the present 10 minute interval.

WRITELOCAL:

Writes all current information to the local display.

WRITEDATA:

Writes data to archive over the network.

WRITEBACKUP:

Writes data to local redundant storage.

5.5 Data Files and Interpretation

Data files in the archive are saved hourly using the following naming convention:

(two digit year), (three digit Julian day), “h”, (two digit hour), “.CSV”

Example: The data file from 10:00:00 pm to 10:59:59 pm on March 25, 2001 would be “01084h22.csv.”

Figure 5.3 is the beginning of a typical data file. The columns contain the following data:

Column 1: Minute and second within the hour according to the datasystem clock

Column 2: Voltage from the differential pressure sensor (volts)

Column 3: Calculated windspeed (miles per hour)

Column 4: Voltage from the temperature transmitter (volts) (included once per minute)

Column 5: Calculated temperature (degrees F) (included once per minute)

Column 6: Total pressure (kPa) (included once per minute)

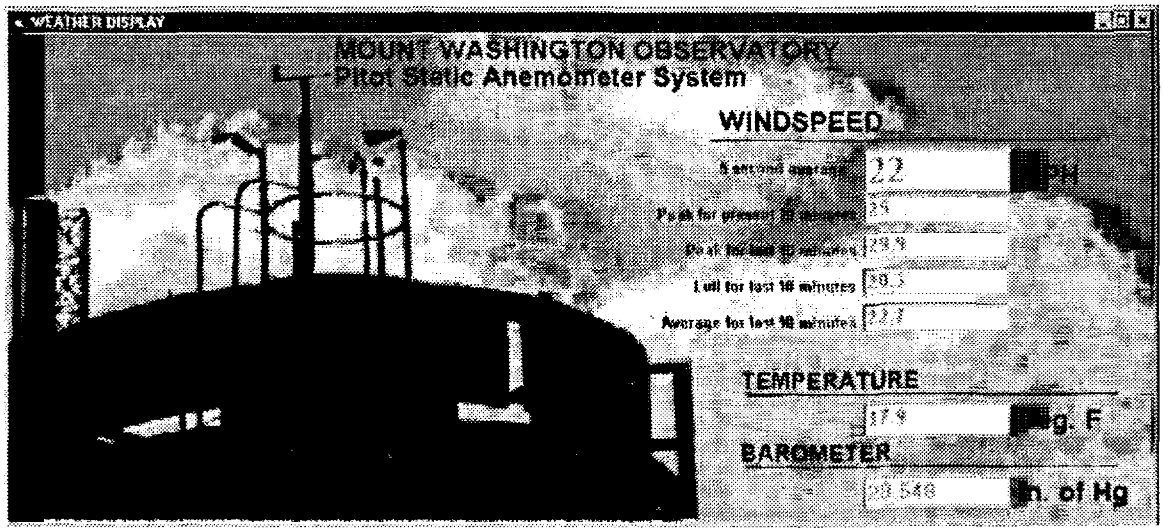
Figure 5.3 Example Data File

```
99356H09.CSV
PITOT-STATIC ANEMOMETER AND PAROSCIENTIFIC
BAROMETER
DATA FILE FOR DATE 12-22-1999
(JULIAN DAY:  356 )
START TIME: 09:00:00
       0:01   0.06702        21.6   1.30357         -45.1   101.5686
       0:01   0.06644        21.5
       0:02   0.06687        21.6
       0:03   0.06704        21.6
       0:04   0.06653        21.5
```

5.6 Weather Wall Display

The Weather Wall display is a Visual BASIC program that presents the last data taken by the datasystem in real time. It is simply a picture with text boxes on it where the data are displayed. A sample screen is illustrated in Figure 5.4:

Figure 5.4 Sample Display Screen



The fields on the display, from top to bottom are as follows:

- 5 second running average windspeed.

Each hour is divided into six 10 minute intervals (ex. 1:00:00 to 1:09:59, 1:10:00 to 1:10:59, etc.) For these intervals, the following information is displayed:

- Peak windspeed for the current 10 minute interval
- Peak windspeed for the previous 10 minute interval

- Lowest windspeed for the previous 10 minute interval
- Average windspeed for the previous 10 minute interval

Once per minute, the following information is updated:

- Current air temperature in degrees Fahrenheit
- Current barometric pressure in inches of mercury

5.7 Display Software Configuration

The display is a Visual Basic program that reads a single line of data from the file "DISPLAY.TXT." This file resides in the directory where the datasystem stores data. The executable file is "DISPLAY.EXE." When this program starts, it opens the file "DISPLAYPATH.TXT" that must be in the same directory as the executable. This file contains a single string, the path to DISPLAY.TXT. An example file is shown in Figure 5.5.

Figure 5.5 Example DISPLAYPATH.TXT File

```
H:\DATA\DISPLAY.TXT
```

Thus the directory where the datasystem stores its data must also be mapped as a drive on the machine that runs the display program.

Once DISPLAYPATH.TXT has been configured, the display program can be started and resized to look nice on the screen.

Chapter 6

Results and Conclusion

At the time of this writing, the DOS based system has been in operation and collecting data for one year. This has given the observers a chance to use the system and evaluate its functionality and reliability. The conclusion is that while the instantaneous data is useful, the observers would like the averaging routine to be updated. This is purely a software issue; it has no bearing on the actual measurements. The hardware functions flawlessly. For the first time the Observatory has research grade instruments for measuring windspeed, temperature and barometric pressure.

The errors associated with this anemometer are more complicated than a simple percentage. The effects of different errors change with the absolute windspeed, atmospheric pressure, and temperature. Fortunately, as the windspeed increases the measurement becomes more accurate for a given differential pressure accuracy. This holds true until approximately 300 mph, after which the errors from the temperature sensor and barometer begin to take over. For all windspeeds between 100 and 250 mph, the indicated windspeed will be accurate to within 2 mph, assuming a perfectly aligned Pitot tube and no leaks in the system.

If a windspeed above 231 miles per hour is ever measured with this instrument, it should be carefully scrutinized. All factors should be taken into account, including variability of the wind, change in wind direction, and the physical condition of the equipment should be examined by a qualified independent laboratory.

The other major issue is reliability of the networking software. As previously stated, this project is beyond the capability of the DOS operating system. As of the time of this writing, the plan is to decommission the embedded computer and connect the instruments to a dedicated data collection Linux desktop PC in the Observatory. This machine will also be connected to the wind vane and will be able to accept data from other devices that have a serial interface.

6.1 Future Work

As stated above, a plan is in place to update the Pitot static anemometer's software. Although the embedded PC is being eliminated from this project, it was a worthwhile exercise in using small PCs to perform a task that is beyond the scope of simpler controllers.

An excellent description of implementing such a system is the Linux Embedded How-to[1], which boots from the hard drive, creates a RAM disk to mount as the root directory, then runs the user program. The disadvantage in this system is that there is not very much room for local data storage.

---

[1] Huet, Sebastien, "Embedded Linux Howto," accessed 22 April, 2001; available from http://www.linux-embedded.org/howto/Embedded-Linux-Howto.html.

A good compromise would be to have the 386 boot from the hard drive and only mount one data storage partition in read-write mode. Thus the operating system is protected from inadvertant crashes and the system can still store a large amount of data locally.

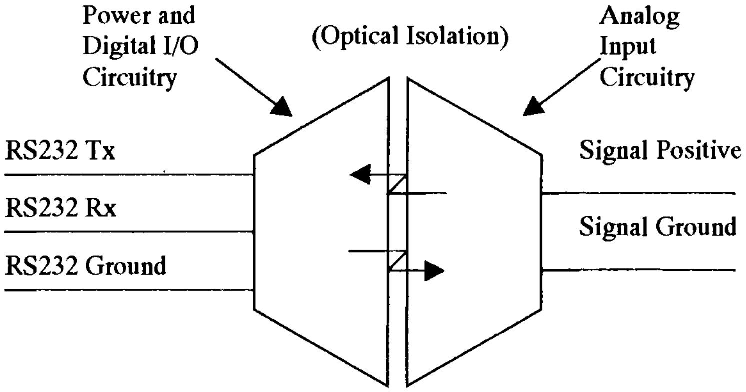
6.2 Vane Assembly

This thesis has not given much attention to the other critical part of the anemometer, the vane assembly that aims the Pitot tube into the wind. This is almost an entirely mechanical device, with the exception of the embedded resistance heaters and thermocouples. Although investigating the vane would be a worthwhile venture, Pitot 92 must be commended for its reliability. It has operated for eight years continuously without heater issues or mechanical failure. Thus it should be used as the standard on which other vanes are judged. Designing a new vane assembly would make an excellent mechanical engineering project.

6.3 Next Generation ADC Box

Although the custom-built ADC has performed flawlessly, an off the shelf unit was located that is suitable for this application. Obviously, an off-the-shelf unit is more desirable for maintenance reasons. The Omega Model D5251 has four 14 bit analog input channels and is reasonably priced at $250. In addition, these modules have full isolation from the analog input side to the power/output side. Figure 6.1 is a block diagram of the Omega Model D5251.

Figure 6.1 Omega ADC Module



Disassembling the unit revealed a 68HC705 processor, a small switching power supply for the isolated circuitry, an Analog Devices AD654JN voltage to frequency converter as the ADC, and a HCF4051 eight input analog multiplexer.

The next generation ADC will improve performance by isolating the measurement, effectively increasing the common mode rejection ratio. One of the challenges of designing electronics for use on Mount Washington is the large amount of radio interference that is continually present and shows up as common mode noise in every piece of equipment in the Observatory. Natural sources are lightning and charged clouds. (The author once sat on the concrete tower and held one lead of an AC circuit tester to a grounded pipe while touching the other lead; the light glowed brightly from the static in the cloud!) Man-made sources are at least ten computers in the Observatory that run continuously and the multitude of television and radio antennas on the summit. Incorporating this ADC will further contribute to reliable, accurate performance in this challenging research environment.

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Appendix A
Foxboro Calibration Data

Table A.1 Calibration Regression

SUMMARY OUTPUT: regression analysis of a 1% sample of Foxboro vs. Barocel pressure data taken between 1/7/99 and 1/30/99

Regression Statistics	
Multiple R	0.99511524
R Square	0.99025435
Adjusted R Square	0.99025375
Standard Error	0.07308738
Observations	16384

ANOVA

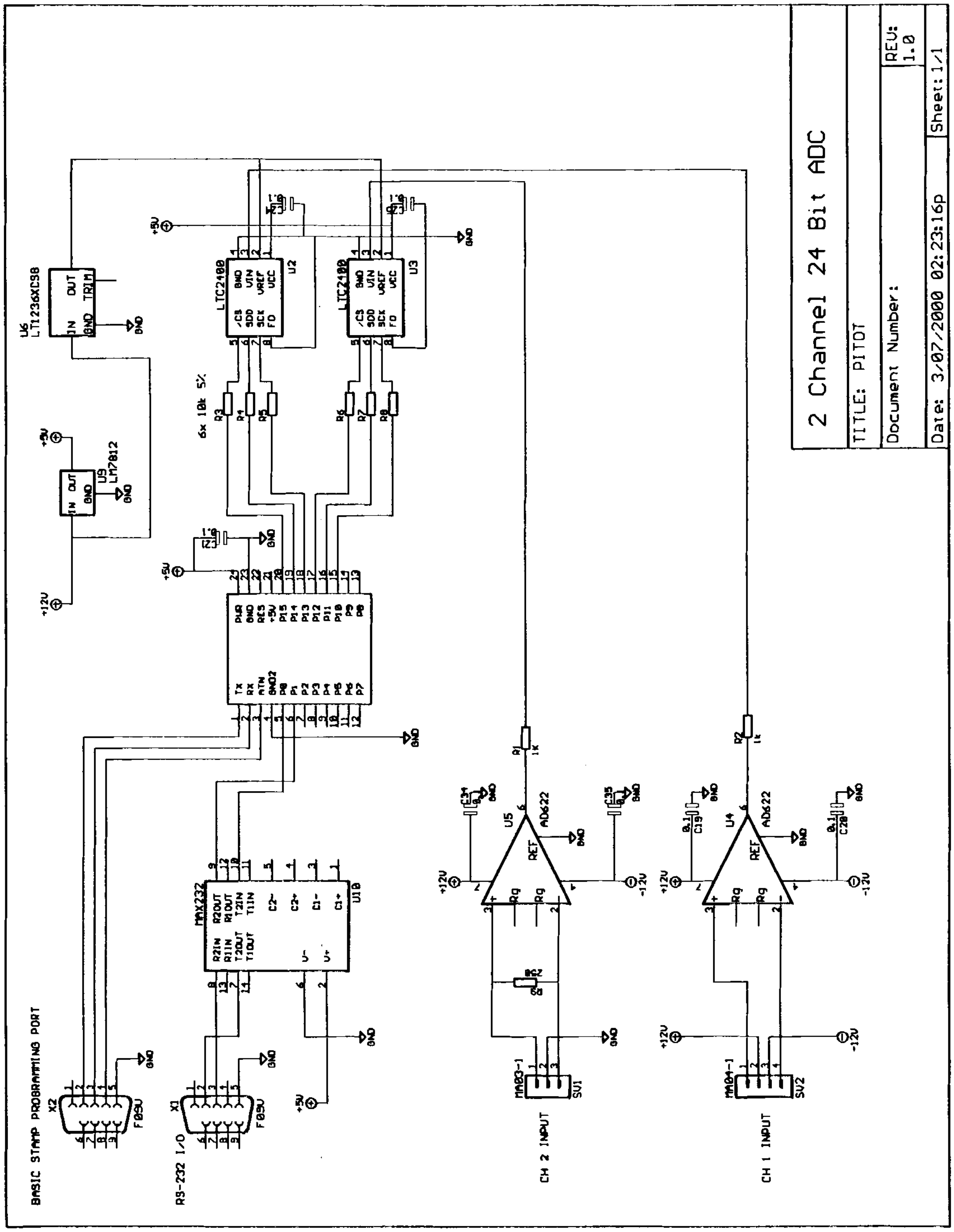
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	8891.7585	8891.7585	1664572.89	0
Residual	16382	87.5088072	0.00534177		
Total	16383	8979.26731			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-0.68526	0.00155	-442.62472	0.00000
X Variable 1	14.71377	0.01140	1290.18328	0.00000

Lower 95%	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
-0.68829	-0.68222	-0.68829	-0.68222
14.69142	14.73613	14.69142	14.73613

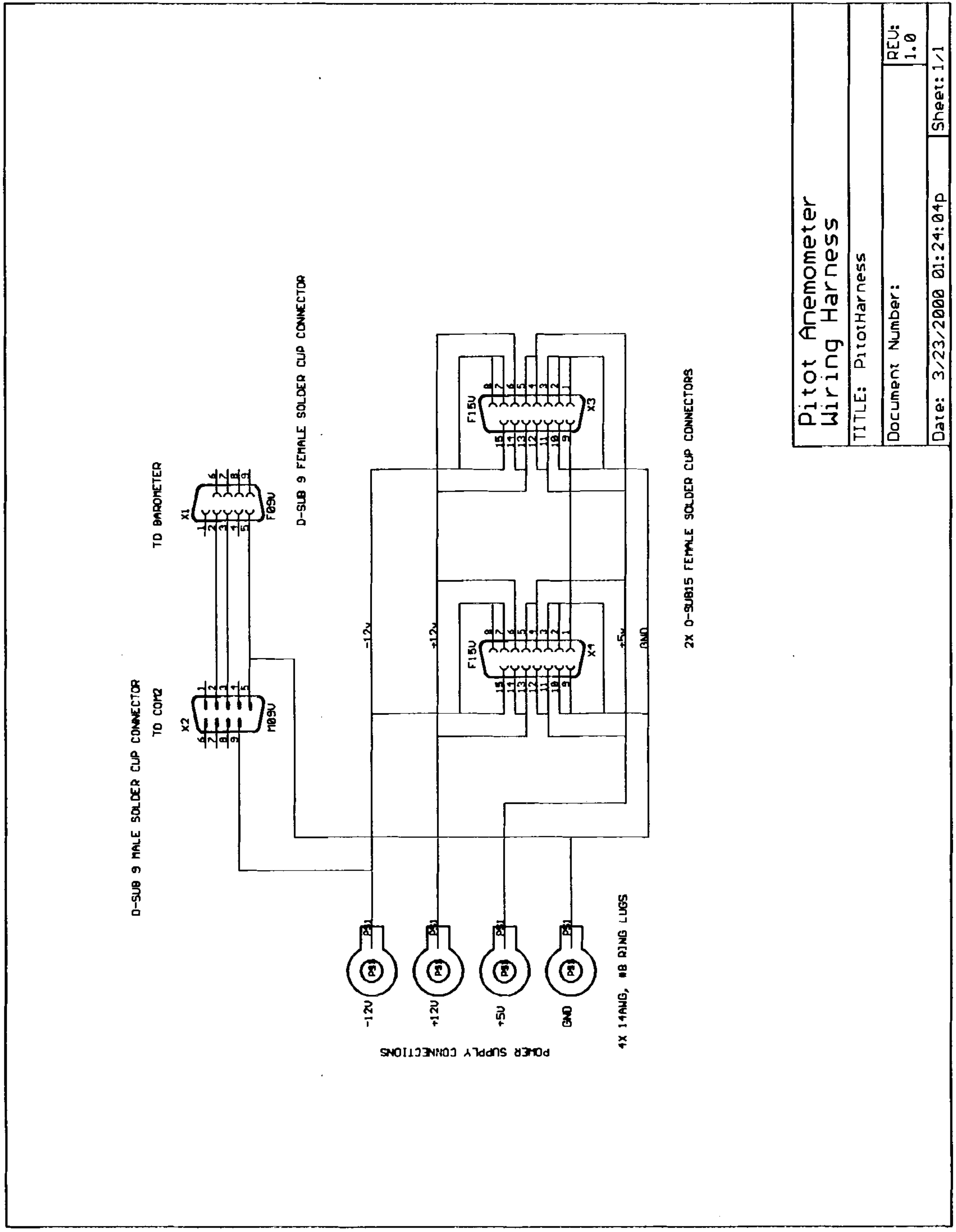
Appendix B
ADC Schematic

Figure B.1 ADC Schematic



Appendix C
Wiring Harness Schematic

Figure C.1 Wiring Harness Schematic



Appendix D
Main Program Source Code

```
'REV 20 - FINAL CLEANUP! ALSO ADD NET SHUTDOWN CAPABILITY.

'RESERVED FILE NUMBERS:
'1 - COM1 FOR VOLTAGE MEASREMENT
'2 - COM2 FOR PARO READINGS
'3 - REMOTE DATA FILE
'4 - LOCAL BACKUP DATA FILE

DECLARE SUB INITIALIZE ()
DECLARE SUB GETPARAMS ()
DECLARE SUB NEWHOUR ()
DECLARE SUB NEWBACKUP ()
DECLARE SUB GETVOLTS ()
DECLARE SUB GETTEMP ()
DECLARE SUB GETWSPEED ()
DECLARE SUB GETAVG ()
DECLARE SUB WRITEDATA ()
DECLARE SUB WRITELOCAL ()
DECLARE SUB WRITEBACKUP ()
DECLARE SUB GETTOTALPRESSURE ()
DECLARE SUB SETTOTALPRESSURE ()
DECLARE SUB MAKEBACKUPS ()

DECLARE FUNCTION JULIANDAY ()
DECLARE FUNCTION FILE$ ()

COMMON SHARED NETPATH$, BACKFILE$, TIMESERVER$, CH1, CH2
COMMON SHARED CH1ZERO, CH2ZERO, CH1SPAN, CH2SPAN, DENSITY
COMMON SHARED TEMP, PTOTAL, WSPEED, AVG5SEC, LAST15AVG,
THIS15TOTAL
COMMON SHARED LAST15MAX, THIS15MAX
DIM SHARED LAST5SEC(5)
DIM SHARED NETGOOD, REMEMBERHOUR AS INTEGER
DIM SHARED REMEMBER15, COUNTER5, THIS15COUNT AS INTEGER

MAIN:
 INITIALIZE
 GETPARAMS
 NEWHOUR
 NEWBACKUP

 DO
   STARTTIME = INT(TIMER)
```

```
  SELECT CASE UCASE$(INKEY$)
       CASE "Q"
       GOTO QUIT
       CASE "N"
       NETGOOD = 1: NEWHOUR
       CASE "L"
       NETGOOD = 0: CLOSE #3
       CASE "B"
       MAKEBACKUPS
  END SELECT

 IF INT(VAL(MID$(TIME$, 1, 2))) <> REMEMBERHOUR THEN  'DETECT NEW
HOUR
    CLOSE #4: NEWBACKUP
    IF NETGOOD = 1 THEN
      CLOSE #3: NEWHOUR
    END IF
  END IF

  GETVOLTS
  GETTEMP  'REM THIS LINE FOR TEST WITHOUT FOX. TEMP SENSOR
' TEMP = 0 'UN-REM THIS LINE FOR TEST
  GETWSPEED
  GETAVG
  WRITELOCAL
  IF NETGOOD = 1 THEN WRITEDATA
  WRITEBACKUP
  COUNTER1 = COUNTER1 + 1
  DO WHILE INT(TIMER) = STARTTIME: LOOP
 LOOP

STOP
END



GETTOTALPRESSURE:
 COM(2) OFF
 RTIME = TIMER: DO WHILE TIMER - RTIME < .1: LOOP  'WAIT 1/10 SECOND
 INPUT #2, PTOTAL$
 PTOTAL = VAL(MID$(PTOTAL$, 6))
 COUNTER2 = COUNTER2 + 1
 PARODATAFLAG = 1
 COM(2) ON
RETURN
```

```
HANDLER:
 CLS
 PRINT "ERROR: ", ERR
 PRINT "FROM DEVICE: ", ERDEV$
RESUME NEXT

QUIT:
DO WHILE FREEFILE > 1
 CLOSE (FREEFILE - 1)
LOOP

STOP
END

FUNCTION FILE$

 SELECT CASE JULIANDAY
  CASE 1 TO 9
   DAY$ = "00" + LTRIM$(STR$(JULIANDAY))
  CASE 10 TO 99
   DAY$ = "0" + LTRIM$(STR$(JULIANDAY))
  CASE 99 TO 366
   DAY$ = LTRIM$(STR$(JULIANDAY))
 END SELECT


 FILE$ = MID$(DATE$, 9, 2) + DAY$ + "H" + MID$(TIME$, 1, 2) + ".CSV"

END FUNCTION

SUB GETAVG
'**** COMPUTE 5 SECOND RUNNING AVERAGES,
'**** 15 MINUTE AVERAGE EVERY 15 MINUTES
COUNTER5 = COUNTER5 + 1
IF COUNTER5 > 4 THEN COUNTER5 = 0
LAST5SEC(COUNTER5) = WSPEED

AVG5SEC = 0
FOR I = 0 TO 4
 AVG5SEC = AVG5SEC + (LAST5SEC(I) / 5)
NEXT

 AVG5SEC = INT(AVG5SEC * 10) / 10   'LIMIT TO 1 DECIMAL PLACE
```

```
 IF AVG5SEC > THIS15MAX THEN THIS15MAX = AVG5SEC

IF INT(TIMER / 900) <> REMEMBER15 THEN
  LAST15AVG = THIS15TOTAL / THIS15COUNT
  LAST15AVG = INT(LAST15AVG * 10) / 10  'LIMIT TO 1 DECIMAL PLACE
  THIS15TOTAL = 0: THIS15COUNT = 0
  REMEMBER15 = INT(TIMER / 900)    'WHICH 15 MINUTE INTERVAL

  LAST15MAX = THIS15MAX
  THIS15MAX = 0

END IF

THIS15COUNT = THIS15COUNT + 1
THIS15TOTAL = THIS15TOTAL + WSPEED

END SUB

SUB GETPARAMS

FILENUM = FREEFILE
OPEN "PARAMS.TXT" FOR INPUT AS #FILENUM
   LINE INPUT #FILENUM, NETPATH$
   LINE INPUT #FILENUM, TIMESERVER$
   INPUT #FILENUM, CH1ZERO
   INPUT #FILENUM, CH1SPAN
   INPUT #FILENUM, CH2ZERO
   INPUT #FILENUM, CH2SPAN
CLOSE #FILENUM



END SUB

SUB GETTEMP

'SUBROUTINE TO CALCUALTE TEMPERATURE FROM FOXBORO
TRANSMITTER
'4 - 20 mA = -60 TO 80 DEG. F = -51 TO 27 DEG. C

TEMP = -51 + ((CH2 - 1) * (78 / 4))  'DEGREES CENTIGRADE
TEMP = INT(TEMP * 10) / 10           'LIMIT TO 1 DECIMAL PLACE
END SUB

SUB GETVOLTS
 FILENUM = FREEFILE
```

```
OPEN "COM1:9600,N,8,1,CS,DS,LF,TB1,RB10" FOR RANDOM AS #FILENUM
PRINT #FILENUM, "1"
INPUT #FILENUM, CH1$
RTIME = TIMER: DO WHILE TIMER - RTIME < .1: LOOP  'WAIT 1/10 SECOND
PRINT #FILENUM, "2"
INPUT #FILENUM, CH2$
CLOSE #FILENUM

'CALCULATE VOLTAGES FROM BINARY WORD
CH1$ = "&H" + CH1$
CH1 = VAL(CH1$)
CH1 = CH1 - &H20000000
CH1 = CH1 / 268435456
CH1 = CH1 * 5
CH1 = INT(CH1 * 100000) / 100000  'LIMIT TO 0.01 mV RESOLUTION

CH2$ = "&H" + CH2$
CH2 = VAL(CH2$)
CH2 = CH2 - &H20000000
CH2 = CH2 / 268435456
CH2 = CH2 * 5
CH2 = INT(CH2 * 100000) / 100000  'LIMIT TO 0.01 mV RESOLUTION


END SUB

SUB GETWSPEED

'********** CALCULATE SETRA PRESSURE **********
PSETRA = (CH1 + CH1ZERO) * 1492.98
IF PSETRA < .001 THEN
PSETRA = 0
END IF

'CALCULATE WINDSPEED
DENSITY = PTOTAL / ((TEMP + 273) * .287)'REPLACE 273 WITH ABS. TEMP IN
KELVIN
IF DENSITY < .01 THEN DENSITY = .5        'AVOID DIV BY 0 CRASH

WSPEED = SQR(2 * PSETRA / DENSITY)        'METERS/SECOND
WSPEED = WSPEED * 2.2369                  'MILES/HOUR
WSPEED = INT(WSPEED * 10) / 10            'LIMIT TO 2 DECIMAL PLACES
IF WSPEED > 215 THEN WSPEED = 215
END SUB

SUB INITIALIZE
```

```
 '********** CLEAR SCREEN, START PARO,              **********
 '********** ENABLE COM(2) TRAPPING, INIT COUNTERS AND FLAGS
**********
 '********** OPEN LOCAL DATA FILE

 CLS

 OPEN "COM2:9600,N,8,1,CS,DS,LF,TB256,RB256" FOR RANDOM AS #2
 PRINT #2, "*0100VR"   'STOP PARO
 PRINT #2, "*0100P4"   'PARO SEND CONTINUOUSLY
 COM(2) ON
 ON COM(2) GOSUB GETTOTALPRESSURE
 ON ERROR GOTO HANDLER
 NETGOOD = 1
 BACKUPRECORD = 1
 PARODATAFLAG = 0
 LAST15AVG = 0
 THIS15TOTAL = 0
 THIS15COUNT = 0
 LAST15MAX = 0
 REMEMBER15 = INT(TIMER / 900)    'WHICH 15 MINUTE INTERVAL
 COUNTER1 = 0
 COUNTER2 = 0
 PTOTAL = 75       'INITIALIZE PTOTAL TO NOMINAL VALUE

END SUB

FUNCTION JULIANDAY

  DAY = VAL(MID$(DATE$, 4, 2))  'DAY

  'DETECT LEAP YEAR - THIS WILL FAIL IN YEAR 2400
  IF VAL(MID$(DATE$, 7, 4)) MOD 4 = 0 THEN
      FEBDAYS = 29
      ELSE
      FEBDAYS = 28
  END IF

  SELECT CASE VAL(MID$(DATE$, 1, 2))

      CASE 1  'JANUARY
      JULIANDAY = (DAY)

      CASE 2  'FEBRUARY
      JULIANDAY = (31 + DAY)
      CASE 3  'MARCH
```

```
   JULIANDAY = (31 + FEBDAYS + DAY)
   CASE 4  'APRIL
   JULIANDAY = (31 + FEBDAYS + DAY + 31)
   CASE 5  'MAY
   JULIANDAY = (31 + FEBDAYS + DAY + 61)
   CASE 6  'JUNE
   JULIANDAY = (31 + FEBDAYS + DAY + 92)
   CASE 7  'JULY
   JULIANDAY = (31 + FEBDAYS + DAY + 122)
   CASE 8  'AUGUST
   JULIANDAY = (31 + FEBDAYS + DAY + 153)
   CASE 9  'SEPTEMBER
   JULIANDAY = (31 + FEBDAYS + DAY + 184)
   CASE 10 'OCTOBER
   JULIANDAY = (31 + FEBDAYS + DAY + 214)
   CASE 11 'NOVEMBER
   JULIANDAY = (31 + FEBDAYS + DAY + 245)
   CASE 12 'DECEMBER
   JULIANDAY = (31 + FEBDAYS + DAY + 275)
  END SELECT

END FUNCTION

SUB MAKEBACKUPS

CLS
PRINT "THIS OPERATION WILL COPY BACKUP FILES TO THE NETWORK."
PRINT "CONTINUE?"

INPUT REPLY$
IF UCASE$(REPLY$) = "Y" THEN

PRINT "COPY C:\DATA\*.* " + MID$(NETPATH$, 1, (LEN(NETPATH$) - 1))

SHELL "COPY C:\DATA\*.* " + MID$(NETPATH$, 1, (LEN(NETPATH$) - 1))
END IF

END SUB

SUB NEWBACKUP

 BACKFILE$ = "C:\DATA\BACKUP" + MID$(TIME$, 1, 2) + ".BAK"
 OPEN BACKFILE$ FOR OUTPUT AS #4
 PRINT #4, FILE$
 PRINT #4, "PITOT-STATIC ANEMOMETER AND PAROSCIENTIFIC
BAROMETER"
```

```
 PRINT #4, "DATA FILE FOR DATE "; DATE$
 PRINT #4, "(JULIAN DAY:  "; JULIANDAY; ")"
 PRINT #4, "START TIME: "; TIME$

END SUB

SUB NEWHOUR
 PRINT "ENTERING NEWHOUR SUB"
 RTIME = TIMER: DO WHILE TIMER - RTIME < .25: LOOP  'WAIT 1/4 SECOND

 OPEN NETPATH$ + FILE$ FOR APPEND AS #3
 IF LOF(3) > 10 THEN GOTO NOHEADER
 PRINT #3, FILE$
 PRINT #3, "PITOT-STATIC ANEMOMETER AND PAROSCIENTIFIC
BAROMETER"
 PRINT #3, "DATA FILE FOR DATE "; DATE$
 PRINT #3, "(JULIAN DAY: "; JULIANDAY; ")"
 PRINT #3, "START TIME: "; TIME$

NOHEADER:


 REMEMBERHOUR = INT(VAL(MID$(TIME$, 1, 2)))

 IF MID$(TIME$, 1, 2) = "00" THEN       'SYNC TIME AT MIDNIGHT
   SHELL "NET TIME \\" + TIMESERVER$ + " /SET /Y "


 END IF

END SUB

SUB WRITEBACKUP

'**********WRITE TO LOCAL 24 HR BACKUP FILE, SAME INFO AS MAIN
DATA FILE**********


  IF INT(TIMER) MOD 60 = 0 THEN
    WRITE #4, MID$(TIME$, 4, 5), CH1, WSPEED, CH2, TEMP, PTOTAL
  ELSE
    WRITE #4, MID$(TIME$, 4, 5), CH1, WSPEED
  END IF

PRINT "LOCAL BACKUP FILE: "; BACKFILE$
```

```
END SUB

SUB WRITEDATA

 '********WRITE TO DATAFILE, INCLUDE ABS. PRESSURE ONCE PER
MINUTE *******
 '********FORMAT: TIME(MM:SS), WINDSPEED, CH1 VOLTAGE, CH2
VOLTAGE,*******
 '********        WINDSPEED, TEMPERATURE, BAROMETRIC PRESSURE
*******

  PRINT "APPENDING FILE "; NETPATH$; FILE$; " WITH:"

  IF INT(TIMER) MOD 60 = 0 THEN
   WRITE #3, MID$(TIME$, 4, 5), CH1, WSPEED, CH2, TEMP, PTOTAL
   PRINT MID$(TIME$, 4, 5), CH1, WSPEED, CH2, TEMP, PTOTAL

  ELSE
   WRITE #3, MID$(TIME$, 4, 5), CH1, WSPEED
   PRINT MID$(TIME$, 4, 5), CH1, WSPEED
  END IF


 '**********WRITE TO DISPLAY FILE**********
DISPLAY:
  FILENUM = FREEFILE
  OPEN NETPATH$ + "DISPLAY.TXT" FOR OUTPUT AS #FILENUM
  WRITE #FILENUM, TIME$, AVG5SEC, THIS15MAX, LAST15MAX,
LAST15AVG, TEMP, PTOTAL, FILE$
  CLOSE #FILENUM
  PRINT "REMOTE DISPLAY INFORMATION:"
  PRINT TIME$; AVG5SEC; THIS15MAX; LAST15MAX; LAST15AVG; TEMP;
PTOTAL; FILE$
  PRINT
END SUB

SUB WRITELOCAL

 '**********WRITE TO SCREEN FIRST**********
  CLS
  PRINT "MOUNT WASHINGTON OBSERVATORY ANEMOMETER SYSTEM
LOCAL DISPLAY"
  PRINT "HIT 'Q' TO QUIT, 'L' TO STORE LOCALLY ONLY (NOT TO NETWORK)"
  PRINT "HIT 'N' TO RESUME WRITING TO THE NETWORK"
  PRINT "HIT 'B' TO COPY LOCAL BACKUP FILES TO THE NETWORK"
```

```
 PRINT
 PRINT "CH1 VOLTAGE"; CH1, " CH2 VOLTAGE"; CH2
 PRINT "WINDSPEED FROM SETRA--------------------------"; WSPEED; " MPH"
 PRINT "PRESENT 5 SECOND AVERAGE----------------------"; AVG5SEC; " MPH"
 PRINT "MAXIMUM 5 SEC AVG FOR PRESENT 15 MIN INTERVAL--";
THIS15MAX; " MPH"
 PRINT "MAXIMUM 5 SEC AVG FOR LAST 15 MIN INTERVAL-----";
LAST15MAX; " MPH"
 PRINT "LAST 15 MINUTE AVERAGE-------------------------"; LAST15AVG; " MPH"
 PRINT "AIR TEMPERATURE--------  "; TEMP; " C, ("; 1.8 * TEMP + 32; " F)"
 PRINT "BAROMETRIC PRESSURE----"; PTOTAL; " KPa"
 PRINT "AIR DENSITY------------"; DENSITY; " Kg/m^3"
 PRINT "TIME------------------"; TIME$

 PRINT
END SUB
```

Biography of the Author

Mark Thoren was born in Columbus, Ohio on October 23, 1973. He grew up in Bethel, Connecticut and graduated from Bethel High School in June, 1992. He entered the University of Maine in the fall of 1992 as a Forest Engineering major, but switched to Bio-Resource Engineering shortly after.

In December of 1997 he returned to the University of Maine and enrolled in the Electrical Engineering masters program. He worked both as a research assistant in the Robust Instrumentation Laboratory and as a teaching assistant in the Electrical Engineering Technology program. His main interest is analog and digital curcuit design for mechanical instrumentation. His outside interests include hiking and taking apart whatever he can get his hands on to see how it works.

Mark is a candidate for the Master of Science degree in Electrical Engineering from The University of Maine in May, 2001.