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Unsteady Aerodynamics Experiment Phase V: Test Configuration and Available Data Campaigns

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D.A. Simms
L.J. Fingersh
D.W. Jager
J.R. Cotrell

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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Introduction

The main objective of the Unsteady Aerodynamics Experiment is to provide information needed to quantify the full-scale, three-dimensional, unsteady aerodynamic behavior of horizontal-axis wind turbines (HAWTs). To accomplish this, an experimental wind turbine configured to meet specific research objectives was assembled and operated at the National Renewable Energy Laboratory (NREL). The turbine was instrumented to characterize rotating-blade aerodynamic performance, machine structural responses, and atmospheric inflow conditions. Comprehensive tests were conducted with the turbine operating in an outdoor field environment under diverse conditions. Resulting data are used to validate aerodynamic and structural dynamics models, which are an important part of wind turbine design and engineering codes. Improvements in these models are needed to better characterize aerodynamic response in both the steady-state post-stall and dynamic- stall regimes.

Much of the effort in the first phase of the Unsteady Aerodynamics Experiment focused on developing required data acquisition systems. Complex instrumentation and equipment was needed to meet stringent data requirements while operating under the harsh environmental conditions of a wind turbine rotor. Once the data systems were developed, subsequent phases of experiments were then conducted to collect data for use in answering specific research questions. A description of the experiment configuration used during Phase V of the experiment is contained in this report.

Background

Test results from previous phases of the Unsteady Aerodynamics Experiment have shown that wind turbines undergo complex aerodynamic reactions when operating in typical atmospheric conditions. All wind turbine design codes are based on aerodynamic forces derived from steady two-dimensional (2-D) wind tunnel airfoil test results. Blade designs are developed assuming steady loading optimization principles. Although these design codes produce accurate predictions on average, instantaneous loads and peak power predictions are often incorrect. For HAWTs, these principles are accurate for low to moderate wind speeds, provided that the inflow remains constant. In reality, the inflow conditions exhibit an extremely complex and dynamic nature. Factors such as atmospheric turbulence, shear across the rotor plane, yawed operation, and blade passage through the tower wake all contribute to constantly changing aerodynamic forces that do not obey steady principles. Resulting unsteady aerodynamic forces can be significantly greater than steady forces. These increased fluctuating forces lead to greater dynamic turbine structural responses and high fatigue stresses. With the trend toward lightweight flexible turbines, unsteady aerodynamic loading has become an even more important consideration in predicting dynamic turbine responses.

In order to bridge this gap between the three-dimensional (3-D), unsteady operating environment and the 2-D, steady design environment, NREL implemented the Unsteady Aerodynamics Experiment measurement program designed to obtain experimental data from the 3-D field environment. Measurements needed to quantify the 3-D effects of field operation include meteorological data, loads, local flow angles, and blade surface pressures. Meteorological instrumentation was configured to obtain wind speed, wind direction, and atmospheric stability measurements upwind of the turbine. Loads, such as power production, teeter impact, low-speed shaft bending and torque, blade root bending, and tower motion, were obtained using various power transducers, load cells, accelerometers, and strain gauges. Two devices have been used to obtain local flow characteristics in front of one of the two blades. A flag assembly measured local flow angles during the earlier phases of the experiment, and 5-hole differential pressure probes were implemented in the latter phases of the experiment to improve the dynamic response of the local flow angle measurement. Lastly, blade surface pressures were first measured at one blade span location, but the measurements were extended to five span locations as the experiment progressed. In addition to various measurement capabilities, two blade designs were tested. A constant-chord zero-twist blade set was used in Phase I and Phase II tests. A constant-chord, optimally twisted blade set was used in Phases III and IV. Future tests are planned for a tapered and twisted blade set. The turbine configuration originally consisted of a three-bladed, rigid hub. The current phase, Phase V, introduced a two-bladed, teetered-hub configuration using the constant-chord, optimally twisted blades.

The Unsteady Aerodynamics Experiment was begun in 1987 (it was initially called the "Combined Experiment") and has been implemented in five phases to date. Phase I planning began in 1987 and produced valuable knowledge and experience with these types of measurements (Butterfield, Musial, and Simms 1992). The instrumentation configuration that resulted in Phase I was used to obtain the Phase II data in the spring of 1989. Untwisted blades were used again in Phase II, and the pressure instrumentation was expanded from one to four span locations. Optimally twisted blades were designed for Phase III of the project, which began in 1993 and resulted in data sets in early 1995. The fourth phase, initiated in late 1995, also used the twisted blades; the flow angle measurements, however, were improved. The instrumentation differences between the Phase II, Phase III, and Phase IV configurations were described by Simms et al. (1999). This report contains information regarding Phase V, which was conducted during 1998. However, the major differences between the various phases of data collection are summarized in Table 1.

This report provides the reader with information related to Phase V data collection. For information regarding Phases II-IV, the reader is referred to Butterfield, Musial, and Simms (1992) and Simms et al. (1999). The tables in the body of this report that describe the channels collected by the data system are based upon the header files that accompany each data campaign. Appendix A provides details of the turbine configuration that could be used to develop models. Detailed descriptions and figures of each component of instrumentation are included in Appendix B. Flow charts illustrate the complete signal path from the measurement source to the resulting data file. Calibration procedures are presented for each instrument. Data processing procedures and the associated input files are described in Appendix B as well. Appendix C contains manufacturer specifications for the instrumentation components summarized in one table. General atmospheric and turbine conditions, instrumentation failures, and observations made during data collection are summarized in Appendix D.

Table 1. Unsteady Aerodynamics Experiment Configuration Differences

	Phase II	Phase III	Phase IV	Phase V
Dates for data collection	4/25/89 - 7/25/92	4/7/95 -6/6/95	4/3/96 - 5/18/96 and 4/29/97 - 5/7/97	6/11/98-6/18/98 and 10/28/98-11/18/98
Blades / hub	Untwisted / rigid	Twisted / rigid	Twisted / rigid	Twisted / teeter
Number of blades	3	3	3	2
Local flow angle (LFA) measurement device	Flag	Flag, 5-Hole Probe (test)	5-Hole Probe	5-Hole Probe
Span locations instrumented with LFA sensors	4	5	5	5
Span locations instrumented with full-chord pressure taps	4	5	5	5
Span locations instrumented with pairs of pressure taps	6	10	10	10
Azimuth angle measurements and rotor speed calculation	Poor	Good	Good	Good
Meteorological instrumentation	Vertical Plane Array	Horizontal and Vertical Shear	Horizontal and Vertical Shear	Horizontal and Vertical Shear
Blade strain gauges / blade root strain gauges	Yes / yes	Yes / yes	No / yes	No / yes
Blade tip and nacelle accelerometers	No	Yes	Yes	Yes
Selections of data during which yaw brake engaged	Yes	No	Yes	Yes
Campaign duration	5 minutes	10 minutes	10 minutes	10 minutes
Boom extension and camera mounted on hub; tufts on suction side of instrumented blade	Yes	No	Yes	Yes
Video	Yes	No	Yes	Yes
Pitch angles (blade tip)	12°	3°, -3°, 8°	3°, -3°, 8°, 12°, -9°	3°, -3°, 8°, 12°, -9°
File naming conventions: • **parked#, d4pb###, and d5pb###: Rotor brake engaged with instrumented blade at either 0° or 180° azimuth** • **slwrot# and d4sr###: Blades feathered with rotor slowly rotating** • **d5y3###: yaw brake engaged throughout campaign, pitch angle of 3°** • **d4pp###, and d5pp###: 'pp' indicates pitch angle, 'm' indicates negative value** • **# indicates numerical order in which data collected**	d6511, d6512, d6521, d6522, d6611,…,d7521, d7522	data1-data19 parked1, parked2, slwrot1, slwrot2 (parked1 and parked2 are 60 second duration)	data20-data112, slwrot4, slwrot5 d403001-d403039, d408001-d408012, d4m3001-d4m3012, d4pb001-d4pb009, d4sr001, d412001, d4m9001	d503003-d503014, d503017-d503040, d5m3001-d5m3004, d5m3008-d5m3014, d508007-d508012, d512001, d5m9001-d5m9006, d5y3001-d5y3002, d5pb012-d5pb022
Number of campaigns	58	23	170	73

Test Facility Description

Location

All atmospheric testing was conducted at NREL's National Wind Technology Center (NWTC), which is located 10 miles north of Golden, Colorado. Winter winds are dominant at this site from a prevailing direction of 292° from true north. Although the local terrain is flat with grassy vegetation extending over 0.8 kilometers (km) upwind, the site is situated about 5 km from the base of the Rocky Mountains, which are located directly upwind. The wind turbine site was unobstructed by other wind turbines or structures.

Test Turbine

The Phase V Unsteady Aerodynamics Experiment test turbine is a modified Grumman Wind Stream 33 shown in Figure 1. It is a 10-m-diameter, two-bladed, downwind, free-yaw turbine equipped with full-span pitch capability that can be manually controlled during the testing to provide fixed-pitch (stall-controlled) operation at any pitch angle desired. The turbine is supported on a guyed-pole tower (0.4064 m in diameter) that is equipped with a hinged base and gin pole to allow it to be tilted down easily. An electric winch is used to lower and raise the system during installation. A manually operated yaw brake was added to allow fixed-yaw operation at arbitrary yaw positions. This yaw-retention system has a strain-gauged link that measured yaw moments when the yaw brake was applied. A mechanical caliper rotor brake system was operated manually from the control shed. This feature also was used to obtain data with the instrumented blade parked at the top of the rotational cycle (0°). A complete listing of turbine specifications may be found in Appendix A.

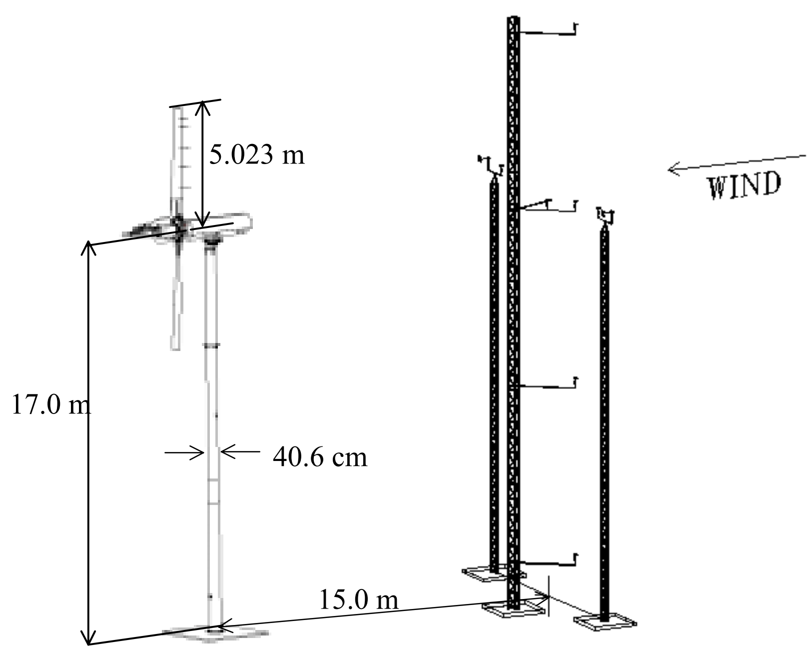


Figure 1. Phase V test configuration

The drive train, pictured in Figure 2, is similar to the original Grumman configuration. The rotor operates at a nominal 72 RPM. Low-speed shaft torque is transferred through a 25.1:1 gearbox ratio to the high-speed shaft which is connected to the 20-kilowatt (kW) induction generator. The drive train (low-speed shaft, gearbox, and high-speed shaft) inertia was determined during Phase IV testing using startup and pendulum tests. An estimate of drive train stiffness was also obtained from this test. Data collected during operation of the instrumented turbine provided measurements of the generator slip and total efficiency of the drive train. The machine description in Appendix A lists all of these results.

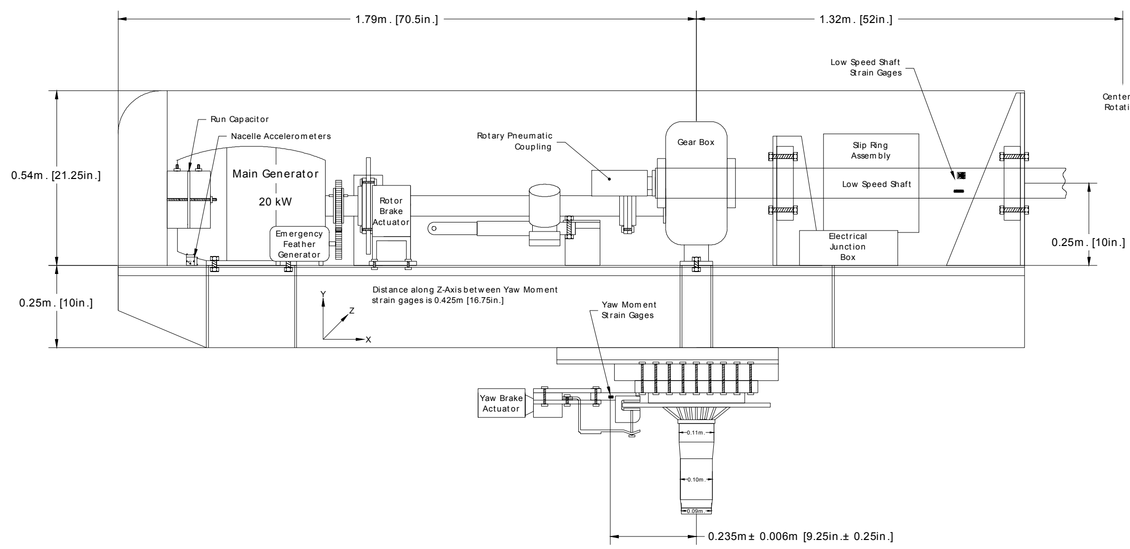


Figure 2. Drive train configuration

The two-bladed, teetered hub was designed specifically for this application (Cotrell 1999). During Phase V, the teeter configuration was maintained, but the hub was designed to be rigid or permit independent blade flap motion. A rigid link between the blades was instrumented with a load cell, and load cells were placed inside the teeter guides to record teeter impact forces. The collective blade pitch system from the original turbine was replaced with servo motors on each blade. The blades can pitch independently or collectively, and the servo motors hold the blades at the specified pitch angle within ±0.1°. Blade pitch control is achieved through software running on a computer in the data shed. Although the turbine has only two blades, the instrumented blade name from previous phases, Blade 3, was maintained for this test.

Another significant configuration change to the original Grumman turbine was the blade design. The NREL S809 airfoil replaced the original Grumman airfoil. The S809 airfoil was developed by Airfoils, Inc., under contract to NREL (Somers 1997). It was optimized to improve wind energy power production and is insensitive to leading-edge roughness. The S809 airfoil has a well-documented wind tunnel database that includes pressure distributions, separation boundary locations, drag data, and flow-visualization data (Somers 1997, Butterfield, Musial, and Simms 1992).

The twisted blades had a constant 0.457-m chord; a planform view of the blades is shown in Figure 3. The intent in the design of the twisted blades was to maintain a constant angle of attack along the span of the blade at a wind speed of 8 m/s (Simms, Fingersh, and Butterfield

1995). The twist distribution is listed in Appendix A and shown in Figure 4. The spar enlargement at the root of the blade extends to 25% span. The blades were fiberglass/epoxy composite, and the spar in the twisted blades was carbon fiber. The blades were designed to be stiff to mitigate aeroelastic blade responses. The dynamic characteristics of the blades were tailored to avoid coalescence of rotor harmonics with flap-wise, edge-wise, and torsional natural frequencies. To minimize the possibility of aeroelastic instabilities, the mass and elastic axes were aligned with the aerodynamic axis. The instrumented blade was painted black to contrast with the white tufts that were used for flow visualization. The pitch shaft on which the blades are mounted is less stiff than the inboard sections of the blade, and most of the flap deflection occurs in this region. For this reason, the pitch shaft must be included in a blade or hub model and is included with the estimated blade mass and stiffness distributions in Appendix A.

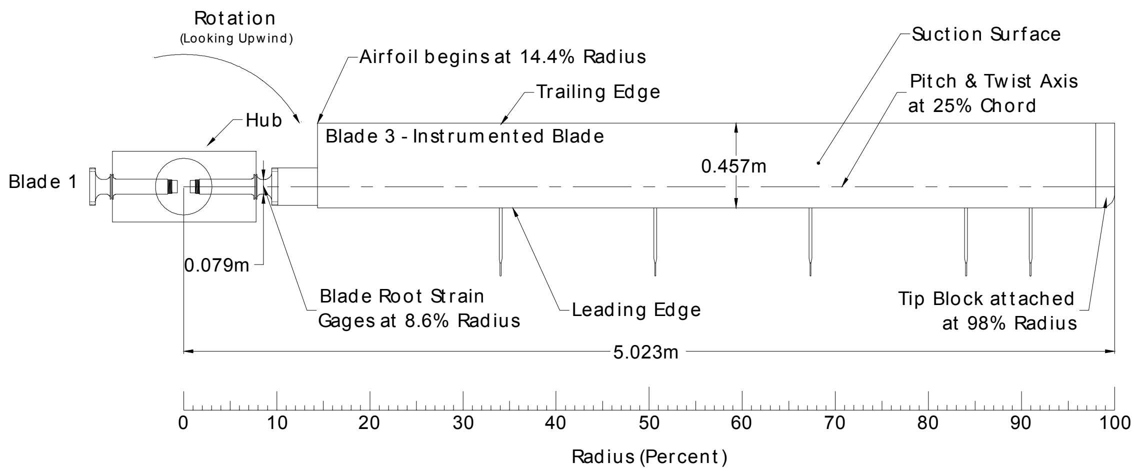


Figure 3. Twisted-blade planform

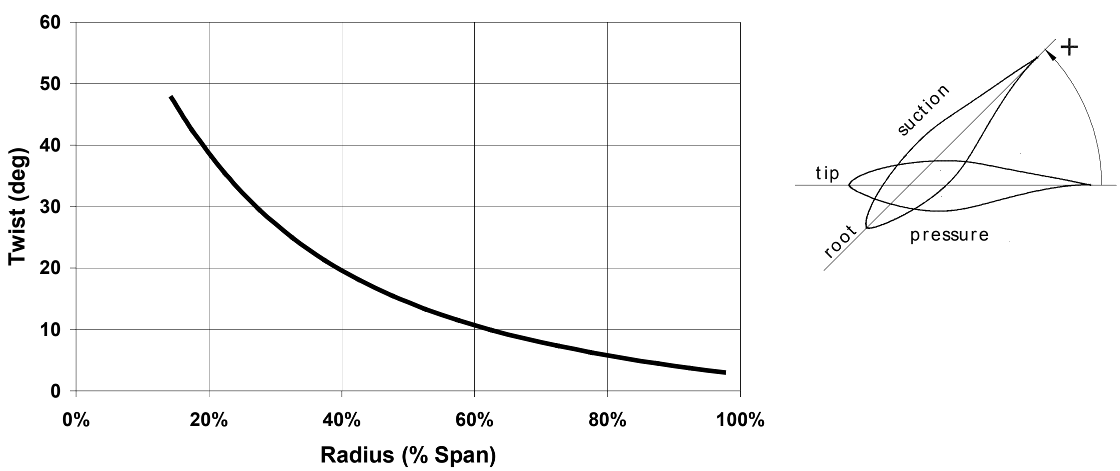


Figure 4. Blade twist distribution at the pitch setting used most frequently during experiment data acquisition: 3° (at tip)

Instrumentation

Meteorological (MET) Towers

Inflow conditions such as shear and stability were measured directly upwind of the turbine. Three MET towers placed 1.5 D (15 m) upwind of the turbine supported multiple cup anemometers, bi-vane anemometers, and one sonic anemometer. Temperature and barometric pressure measurements were also made. Figure 5 shows the three, instrumented, MET towers. Phase V meteorological channel descriptions are shown in Table 2, and detailed instrumentation and wiring information is presented in Appendix B.

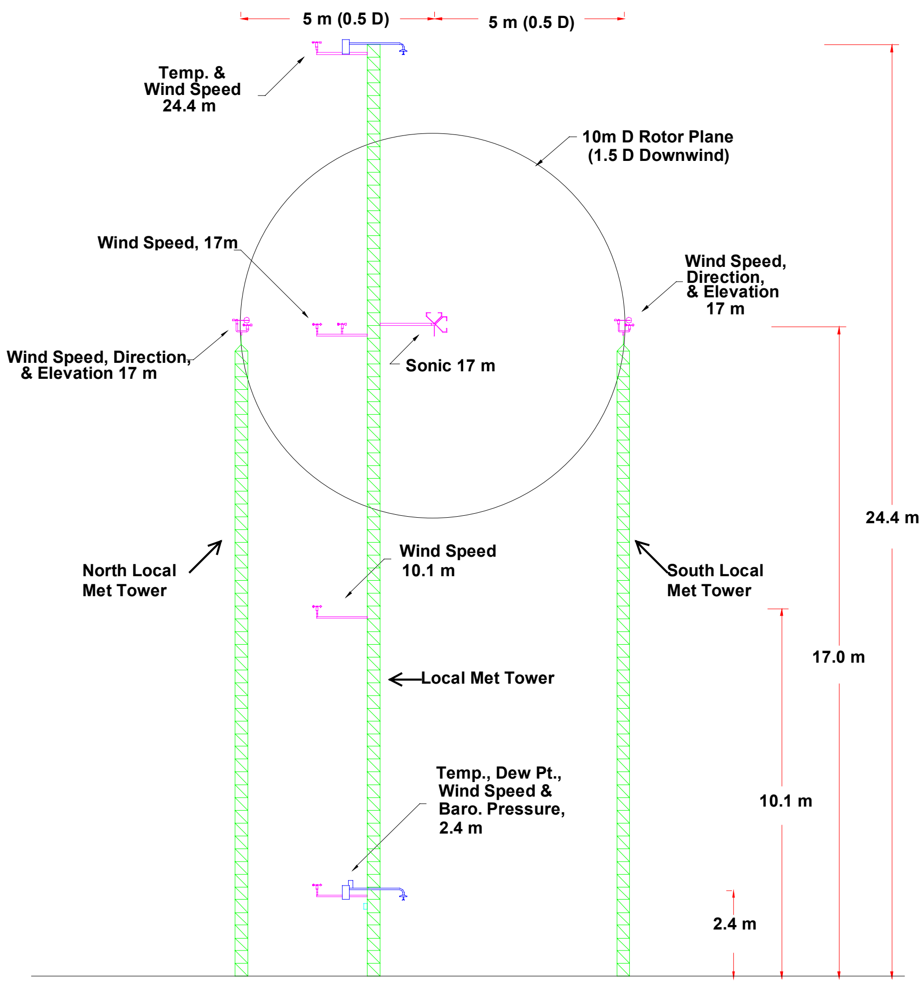


Figure 5. Phase V meteorological instrumentation. Elevation view looking downwind toward 112°. Meteorological instruments are 1.5 D (15 m) upwind of the turbine tower.

Table 2. Local Inflow Measurements

Channel	Channel ID	Description	Units
300	LMWS24M	Local Met Wind Speed 24.38 m	m/s
302	LMWS17M	Local Met Wind Speed 17.02 m (hub height)	m/s
304	LMWS10M	Local Met Wind Speed 10.06 m	m/s
306	LMWS2M	Local Met Wind Speed 2.4 m	m/s
308	NLMWS17M	N local Met Wind Speed 17.02 m (hub height)	m/s
310	NLMWD17M	N local Met Wind Direction 17.02 m (hub height)	deg
312	NLMWE17M	N local Met Wind Elevation 17.02 m (hub height)	deg
314	SLMWS17M	S local Met Wind Speed 17.02 m (hub height)	m/s
316	SLMWD17M	S local Met Wind Direction 17.02 m (hub height)	deg
318	SLMWE17M	S local Met Wind Elevation 17.02 m (hub height)	deg
320	LMT2M	Local Met Temperature 2.4 m	degC
322	LMDT	Local Met Delta Temperature	degC
324	LMDP2M	Local Met Dewpoint 2.4m	degC
326	LMSU17M	Local Met Sonic Channel U 17.02 m	m/s
328	LMSV17M	Local Met Sonic Channel V 17.02 m	m/s
330	LMSW17M	Local Met Sonic Channel W 17.02 m	m/s
334	BARO	Barometric Pressure	Pascal

Pressure Measurements

A variety of pressure measurements yield aerodynamic information. The turbine had one blade (Blade 3) instrumented with pressure taps and 5-hole probes to measure the blade surface pressures and impinging flow angles. The pressure transducers within the blade were all referenced to the pressure inside one of the rotating instrumentation boxes. A digital differential pressure transducer was used to measure the difference between the pressure in this instrumentation box and the static pressure port of a probe upwind of the turbine. In previous phases of the experiment, it was assumed that the pressure inside the rotating instrumentation box was free-stream static pressure. This would permit direct measurement of dynamic pressures. Comparison of the free-stream dynamic pressure obtained through wind speed measurements upwind of the turbine with the dynamic pressures measured on the wind turbine blade showed a consistent offset indicating that the pressure measurements were not referenced to free-stream static pressure. The static pressure probe was then mounted upwind of the turbine in order to measure the difference between the free-stream static pressure and the instrumentation box pressure. This measurement confirmed that the reference pressure inside the instrumentation box was not free-stream static pressure. However, the pressure difference between the upwind static probe and the instrumentation box was not the required magnitude to eliminate the offset between the wind-speed dynamic pressure and the measured dynamic pressure. It was concluded that the upwind probe was influenced by the flow field around the rotor. An empirical correction was derived using the wind-speed estimated dynamic pressure and the measured pressures. Application of this reference pressure correction results in pressure measurements referenced to free-stream static pressure such that the dynamic pressure measurements truly are of the correct magnitude. This correction is explained in the Reference Pressure Correction section of this report, but it was **not** applied to the stored data. The user is responsible for application of this correction.

5-hole Pressure Probes

The 5-hole probe shown in Figure 6 provided dynamic pressure, local flow angle, and spanwise flow angle measurements 0.37 m ahead of the leading edge of the blade. The 5-hole probes were mounted at 34%, 51%, 67%, 84%, and 91% span. The probes were positioned at an angle nominally 20° below the chord line to align the probe with the flow under normal operating conditions. The pressure channels associated with each of the five holes are listed in Table 3. Stainless steel tubes with an outer diameter of 1.6 mm (0.063”) (0.7874 mm (0.031”) inner diameter), carried the probe pressures to the pressure transducer. A short piece of plastic tubing (1.6 mm (0.063”) inner diameter) joined the tubes to the transducers which were mounted inside the blade near the full-chord pressure tap stations.

Each probe was calibrated in a wind tunnel with a 0.914 x 0.914 m (3 x 3 ft) cross section. The probe was mounted in the center of the test section, and pressure data were acquired for angles of attack from -40° to 40°. The probe was then rotated 15° about the probe axis and tested for the same angle of attack range. This was done for roll angles of 0°, 15°, 30°, 45°, 60°, 90°, 120°, 135°, and 150°. The difference between the inboard and outboard pressures was normalized with the tunnel dynamic pressure to correspond with the span-wise flow angle. The difference in pressure between the upper (towards the upper surface of the airfoil) and lower port measurements was normalized with the tunnel dynamic pressure in order to calibrate the local flow angle. The center port pressure normalized with the tunnel dynamic pressure provided the total pressure. These wind tunnel data were input to a neural network model to create surfaces for each of the three probe measurements for all five probes (Fingersh and Robinson 1997). The surfaces were implemented as look-up tables in the post-processing code. The span-wise flow angle and local flow angle channels appear in Table 14 and the dynamic pressure measurements appear in Table 12.

The probe that was mounted at 51% span was not rotated to the appropriate roll angle for one of the runs during the wind tunnel calibration. Data obtained from a different probe at the appropriate roll angle was substituted for the erroneous data prior to use of the neural network. New surfaces for the 51% span probe were generated using the data obtained from another probe at that particular roll angle. These new surfaces were implemented in the processing of all Phase V data.

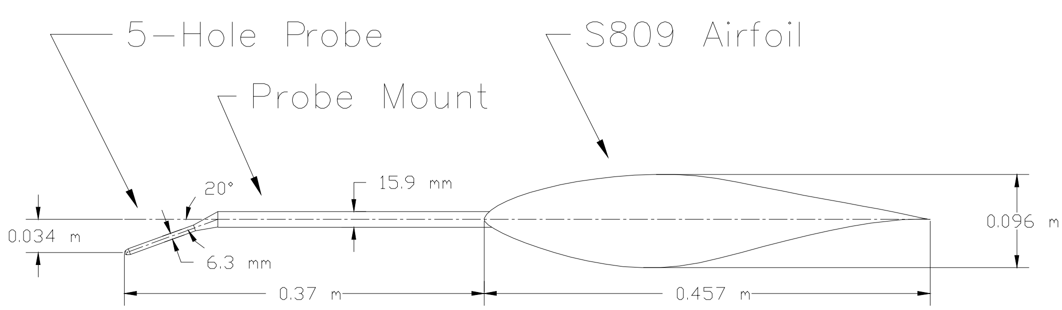


Figure 6. Blade-mounted 5-hole probe

Table 3. 5-Hole Probe Pressures

Channel	Channel ID	Description	Units
052, 053, 152, 153, 252	5HC34, 5HC51, 5HC67, 5HC84, 5HC91	5-hole Center Port 1 (34%, 51%, 67%, 84%, and 91% span)	Pa
054, 055, 154, 155, 254	5HL34, 5HL51, 5HL67, 5HL84, 5HL91	5-hole Lower Port 2 (34%, 51%, 67%, 84%, and 91% span)	Pa
056, 057, 156, 157, 256	5HU34, 5HU51, 5HU67, 5HU84, 5HU91	5-hole Upper Port 3 (34%, 51%, 67%, 84%, and 91% span)	Pa
058, 059, 158, 159, 258	5HO34, 5HO51, 5HO67, 5HO84, 5HO91	5-hole Outboard Port 4 (34%, 51%, 67%, 84%, and 91% span)	Pa
060, 061, 160, 161, 260	5HI34, 5HI51, 5HI67, 5HI84, 5HI91	5-hole Inboard Port 5 (34%, 51%, 67%, 84%, and 91% span)	Pa

Static Probe

During field testing, the static port of a Dwyer 160-U pitot static probe was used to determine the differential between the atmospheric flow field and the instrumentation enclosure to which all blade pressures were referenced. This probe was mounted 2.3 m upwind of the nacelle at hub height when the turbine was operating in a downwind condition. The probe was attached to a vane that aligned itself with the wind as shown in Figure 7. Pressure tubing 1.6-mm (0.063") inner diameter connected the static probe to a rotary pneumatic coupling on the low-speed shaft. The other end of the coupling transferred this pressure to the Mensor digital differential pressure transducer that was open to the rotating instrumentation box (The Mensor output is included in Table 16).

Figure 7. Upwind static probe

Pressure Taps

The most important, yet most difficult, measurements were the blade surface tap pressures. The quality of the aerodynamic performance coefficients depends on the accuracy of individual pressure tap measurements. Aerodynamic coefficients for a particular radial station resulted from the integrated value of the measured pressure distribution. The measurement approach was to install small pressure taps in the surface of the blade skin. Each opening was mounted flush to the airfoil surface. The flush profile was necessary to prevent the taps themselves from disturbing the flow. Stainless-steel tubes with an outer diameter of 1.6 mm (0.7874 mm inner diameter), were installed inside the blade's skin during manufacturing to carry surface pressures to the pressure transducer. A short piece of plastic tubing (1.6 mm inner diameter) joined the tubes to the transducers. To mitigate potential dynamic effects, total tubing length was kept less than 0.45 m (18 in.) by mounting the pressure transducers inside the blade near the pressure tap locations. The taps were aligned along the chord (instead of being staggered) so that span-wise variations in pressure distributions would not distort measured chordwise distributions. As illustrated in Figure 8, the taps were concentrated toward the leading edge to achieve increased resolution in the more active regions of the pressure distributions.

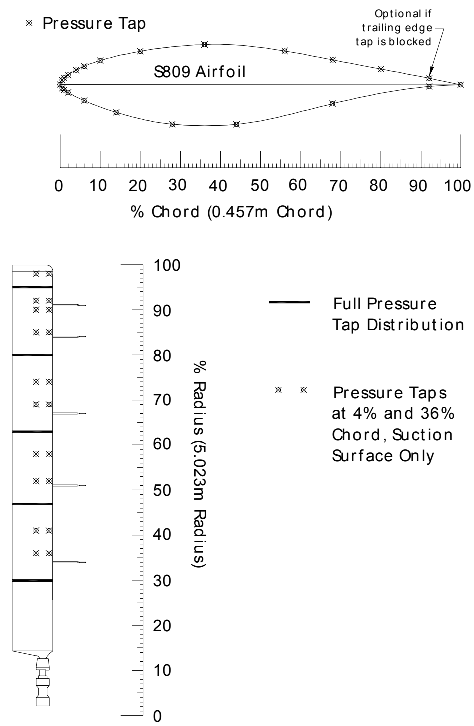


Figure 8. Pressure instrumentation

Twenty two taps were instrumented at five primary span-wise locations: 30% span, 46.6% span, 63.3% span, 80% span, and 95% span. Pairs of taps at 4% chord and 36% chord were installed at various other intermediate span locations (36%, 41%, 52%, 58%, 69%, 74%, 85%, 90%, 92%, and 98%) on the suction surface. These channels are listed in Table 4. The correlation between pressure tap number and airfoil chord location is shown in Table 5. At 63% and 95% span, the trailing edge tap was blocked so the tap at 92% chord on the upper surface (P026392U and P029592U) was instrumented instead. Extrapolation provided an estimate of the trailing edge tap pressure as described in the Derived Channels section. The pressure tap channels contain normalized pressure coefficients as described in the Derived Channels section rather than measured pressures.

Table 4. Pressure Tap Channels

Channel	Channel ID	Description	Units
000-042 (even)	Ptt30ccc	Surface Pressure Coefficients at 30% Span tt = Pressure Tap Number (1, 4, 6, 8, 11, 13, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 27, 31, 32, 34, 36,	Cp
001-043 (odd)	Ptt47ccc	Surface Pressure Coefficients at 47% Span tt = Pressure Tap Number (1, 4, 6, 8, 11, 13, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 27, 31, 32, 34, 36,	Cp
100-142 (even)	Ptt63ccc	Surface Pressure Coefficients at 63% Span tt = Pressure Tap Number (2, 4, 6, 8, 11, 13, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 27, 30, 32, 34, 36,	Cp
101-143 (odd)	Ptt80ccc	Surface Pressure Coefficients at 80% Span tt = Pressure Tap Number (1, 4, 6, 8, 11, 13, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 27, 30, 32, 35, 36,	Cp
200-250 (even)	Ptt95ccc	Surface Pressure Coefficients at 95% Span tt = Pressure Tap Number (2, 4, 6, 8, 11, 13, 15, 17, 18, 19, 20, 21, 22, 23, 24, 25, 27, 30, 32, 34, 36,	Cp
44-51, 144-151, 244-250 (even)	P18ss04U P11ss36U	Intermediate Surface Pressure Coefficients at 36%, 41%, 52%, 58%, 69%, 74%, 85%, 90%, 92%, and 98% Span Pressure Tap Number (11, 18) P118536U was inoperable.	Cp

Table 5. Pressure Tap Chord Locations

Pressure Tap Number	% chord	Surface	tt*	ccc*
1	100%	Trailing edge	01	100
2	92%	Upper	02	92U
4	80%	Upper	04	80U
6	68%	Upper	06	68U
8	56%	Upper	08	56U
10	44%	Upper	10	44U
11	36%	Upper	11	36U
12	28%	Upper	12	28U
13	20%	Upper	13	20U
14	14%	Upper	14	14U
15	10%	Upper	15	10U
16	8%	Upper	16	08U
17	6%	Upper	17	06U
18	4%	Upper	18	04U
19	2%	Upper	19	02U
20	1%	Upper	20	01U
21	0.5%	Upper	21	.5U
22	0%	Leading edge	22	000
23	0.5%	Lower	23	.5L
24	1%	Lower	24	01L
25	2%	Lower	25	02L
26	4%	Lower	26	04L

Table 5. Pressure Tap Chord Locations (continued)

Pressure Tap Number	% chord	Surface	tt*	ccc*
27	6%	Lower	27	06L
28	8%	Lower	28	08L
30	14%	Lower	30	14L
31	20%	Lower	31	20L
32	28%	Lower	32	28L
34	44%	Lower	34	44L
36	68%	Lower	36	68L
38	92%	Lower	38	92L

* See Table 4.

Based on tests performed in Phase I of the experiment, corrections to compensate for dynamic effects on pressure measurements caused by the pressure tap tubing were not applied to measured data sets (Butterfield, Musial, and Simms 1992). Effort was made to mitigate needed corrections by minimizing tubing diameter and keeping tubing length as short as possible. Gain amplifications and phase effects that occur as a function of tube size and length were measured. Results indicated that these effects were not significant up to a frequency of 50 Hertz (Hz), and the measured pressure spectra of a typical data set showed no appreciable information above 50 Hz. Depending on data requirements, it would be possible to process data to remove the dynamic tubing effects. This may become necessary if, for example, a study of high-rate aerodynamic events were to be undertaken.

Pressure Transducer

The dynamic pressure varied significantly along the span of the blade because of rotational effects, so transducers with different measurement ranges were used. The nominal transducer ranges are listed in Table 6. The transducers, Pressure Systems Inc. (PSI) model ESP-32, scanned electronically port to port at 16,666 Hz and completed a scan of all pressure taps at 520.83 Hz. One transducer was used at each primary span location to measure up to 32 differential pressures at the blade surface pressure taps and each of the five ports of a 5-hole probe. These measurements were referenced to the pressure in one of the hub-mounted instrumentation boxes. Corrections were applied to account for the centrifugal force acting on the air column in the pressure tubing as described in the Derived Channel section of the report. Each transducer was installed inside the blade as close to the pressure taps as possible. These electronic scanner-type transducers provided remote calibration capability through a pneumatically operated valve. The capacity to purge all of the pressure taps with dry nitrogen was used periodically to prevent moisture or small particles from affecting the pressure measurements.

Table 6. Nominal, Full-scale, Pressure Transducer Measurement Ranges

30% Span	± 2488 Pa (±10” H_2O)
47% Span	± 2488 Pa (±10” H_2O)
63% Span	± 4977 Pa (±20” H_2O)
80% Span	± 10, 342 Pa (±1.5 psi) during spring 1998; ± 6894 Pa (±1 psi) during fall 1998
95% Span	± 10,342 Pa (±1.5 psi)

Differential pressures between the blade surface pressure and the hub reference pressure were measured by the ESP-32 pressure transducers. For all blade surface pressure measurements as well as probe pressure measurements, the common reference pressure was the pressure inside one of the rotating instrumentation boxes on the hub, which was assumed to be free stream static pressure. Each transducer located in the blade was connected to the reference via a plastic 0.6731 mm inner diameter tube between the hub and the transducer. The hub-mounted instrumentation box was vented to the atmosphere through an orifice on the upwind side of the box. This resulted in a time constant of about 5-10 seconds and provided a relatively stable pressure reference.

Because of the rotation of the pressure tubing, centrifugal forces acting on the column of air contained in the tube change the pressure along the radius of the blade. Each pressure tap measurement was corrected for centrifugal force effects and normalized with the blade stagnation pressure as described in the Derived Channels section that follows. No correction for hydrostatic pressure variation has been applied, although one was proposed by Corten (1998).

A Mensor digital differential pressure transducer was used for two purposes. During pressure calibrations, the Mensor read the pressure difference between the stable, rotating reference pressure (inside the instrumentation box) and the calibration pressure applied by a motorized syringe. During standard operation, the Mensor read the pressure difference between the stable, rotating pressure reference (inside the instrumentation box) and the static pressure port of a pitot static probe mounted upwind of the turbine. Comparison of blade dynamic pressure measurements corrected with this offset and the wind speed estimated dynamic pressure indicate that the probe is not far enough upstream of the turbine to be outside the influence of the rotor. However, this measurement did confirm that the reference pressure for all pressure measurements is not free-stream static pressure as was originally assumed. Table 7 shows the channels corresponding to the digital signal from the Mensor. These are converted into one pressure measurement during post-processing. Two channels are required because the Mensor output is 16 bits, and the data acquisition system is a 12-bit system.

Table 7. Mensor Channels

Channel	Channel ID	Description	Units
259	VBL176	Digital First 12 bits from D pressure	Pa
261	VBL178	Digital Last 12 bits from D pressure	Pa

Comparison of measured blade dynamic pressure versus wind speed estimated dynamic pressure has shown that the reference pressure in the box during Phase II was slightly higher than free stream static pressure. However, similar comparisons in the Phase III, IV, and V data showed that the box reference pressure varied significantly from static pressure. Subsequent direct measurement by the Mensor and the upwind static probe confirmed the result. Therefore, all pressure measurements should be corrected for this reference pressure offset. This proposed correction is described in the "Reference Pressure Correction" section, but it was not applied to the data during post-processing.

During the spring 1998 portion of Phase V, the tubing from the rotary pneumatic coupling to the Mensor was connected to a tee that joined the calibration syringe and the calibration volume chamber (8 in^3) to the Mensor. This resulted in a very slow response for the static pressure measurement. A valve at this junction was added prior to the fall 1998 portion of Phase V to eliminate the additional volume associated with the calibration volume chamber while the turbine was in operation. The static pressure measurement then had a much faster response. The valve was open to the volume chamber and syringe during calibration before and after each campaign.

Pressure System Controller (PSC)

Remote control of ESP-32 pressure transducer calibration, scanner addressing, and demultiplexing of the analog multiplexed signals were performed by the PSC, a hub-mounted microprocessor control unit designed by NREL (Butterfield, Musial, and Simms 1992). The PSC was completely redesigned in subsequent phases to improve the accuracy and the user interface. Currently, up to 155 pressure channels may be processed simultaneously. All pressure ports were scanned at 520.83 Hz. The objective was to provide 100-Hz bandwidth frequency response to enable study of dynamic stall behavior on the rotating wind turbine blade.

Once the PSC scanned the pressure transducers, the samples were digitized, synchronized, and passed to the pulse code modulation (PCM) encoder. The PCM system multiplexed 62 channels of data into one digital data stream, which was conducted through a single coaxial cable. Rotor data were encoded into three PCM streams, which were passed over slip rings to the control building and were recorded on optical disk for subsequent processing.

The PSC pneumatic control valves and ramp calibration sequence is discussed in the Phase I report (Butterfield, Musial, and Simms 1992) and summarized in Appendix B. The only changes between Phase II and later phases were that a more accurate calibration reference pressure was used, and calibrations were automated by a computer-controlled processing system.

Strain Gauges, Accelerometers, and Load Cells

Strain gauges, accelerometers, and load cells were used to measure bending moments, accelerations, and forces in both the rotating and non-rotating environments. Blade flap- and edge-bending moments were recorded from strain gauges mounted at the root (8.6% span) of each blade. Strain gauges on the hub shaft and the low-speed shaft measured bending about two axes and torque. Strain gauges were used to measure yaw moment when the yaw brake was applied. A relatively constant yaw angle and non-zero, fluctuating, yaw moment indicate the yaw brake was engaged during data acquisition. Accelerometers were placed in the nacelle to determine yaw, pitch, and fore-aft motion. Accelerometers were also used in the tips of each blade to measure acceleration in the flap and edge directions. Load cells placed inside the teeter dampers recorded the forces applied during teeter impact. A tension/compression load cell in the link between the blades measured the force between the blades. These measurements are listed in Table 8, and a description of the instrumentation is presented in Appendix B.

The strain gauges measuring root flap and edge loads were applied to the steel pitch shaft adjacent to the blade attachment location. The pitch shaft was reduced to a uniform, cylindrical, 80-mm diameter at 8.6% span, the location where the strain gauges were applied. The uniform, cylindrical region eliminates geometry effects to facilitate accurate measurement of flap- and edge-bending moments. This cylindrical section of the blade root is illustrated in Figure 3 as well as in Appendix B.

Table 8. Load Measurements

Channel	Channel ID	Description	Units
201	B1ACFL	Accelerometer Blade 1-Flap	m/s^2
203	B1ACED	Accelerometer Blade 1-Edge	m/s^2
209	B3ACFL	Accelerometer Blade 3-Flap	m/s^2
211	B3ACED	Accelerometer Blade 3-Edge	m/s^2
215	HSXXB	Strain Hub Shaft XX Bending	N-m
217	HSYYB	Strain Hub Shaft YY Bending	N-m
219	HSTQ1	Strain Hub Shaft Torque 1	N-m
221	HSTQ2	Strain Hub Shaft Torque 2	N-m
223	TLINKF	Strain Teeter Link Force	N
225	B1RFB	Strain Blade 1 Root Flap Bending	N-m
227	B1REB	Strain Blade 1 Root Edge Bending	N-m
229	B1TDAMPF	Strain Blade 1 Teeter Damper Force	N
231	B3TDAMPF	Strain Blade 3 Teeter Damper Force	N
233	B3RFB	Strain Blade 3 Root Flap Bending	N-m
235	B3REB	Strain Blade 3 Root Edge Bending	N-m
237	LSSXXB	Strain X-X LSS Bending	N-m
239	LSSYYB	Strain Y-Y LSS Bending	N-m*
241	LSSTQ	Strain LSS Torque	N-m
336	NAACYW	Nacelle Accelerometer Yaw	m/s^2
338	NAACFA	Nacelle Accelerometer Fore-Aft	m/s^2
340	NAACPI	Nacelle Accelerometer Pitch	m/s^2
342	NAYM	Nacelle Yaw Moment	N-m

* This channel was not operable during the spring 1998 data campaigns.

Miscellaneous Transducers

Gear-driven, BEI model R-25 and RAS-25 optical absolute-position encoders were used to measure yaw position, pitch angle, blade teeter angle, and rotor azimuth position. The yaw position encoder was located near the yaw brake. The rotor azimuth encoder was located in the nacelle on the low-speed shaft. Each blade was provided with an encoder for pitch angle measurement. Figures 9-11 illustrate the measurement conventions.

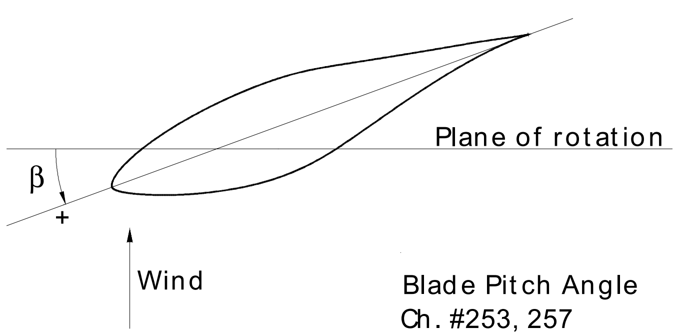


Figure 9. Blade pitch angle orientation

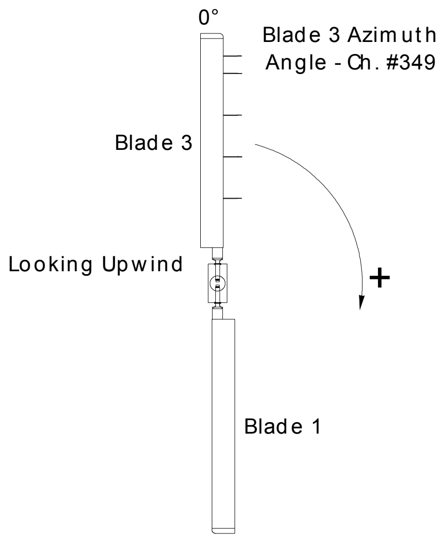


Figure 10. Blade azimuth angle convention

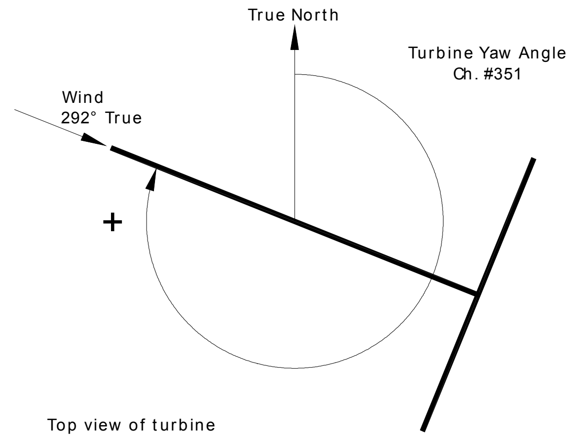


Figure 11. Yaw angle convention

Individual blade flap angles were obtained with an encoder on either side of the teeter pin with an 8:1 gear ratio to improve the accuracy of the small angle measurements. Although the blade cone angle was set at 3.4° downwind, flexibility in the linkage permits slight fluctuation in this angle. Figure 12 illustrates the measurement conventions used. The flap angle encoders permit calculation of the true cone angle as follows:

$$cone = \frac{\phi_3 + \phi_1}{2}, \tag{1}$$

where ϕ_3, and ϕ_1 are the respective blade flap angles. The teeter angle can obtained from the flap angle measurements as follows:

$$teeter = \frac{\phi_3 - \phi_1}{2}. \tag{2}$$

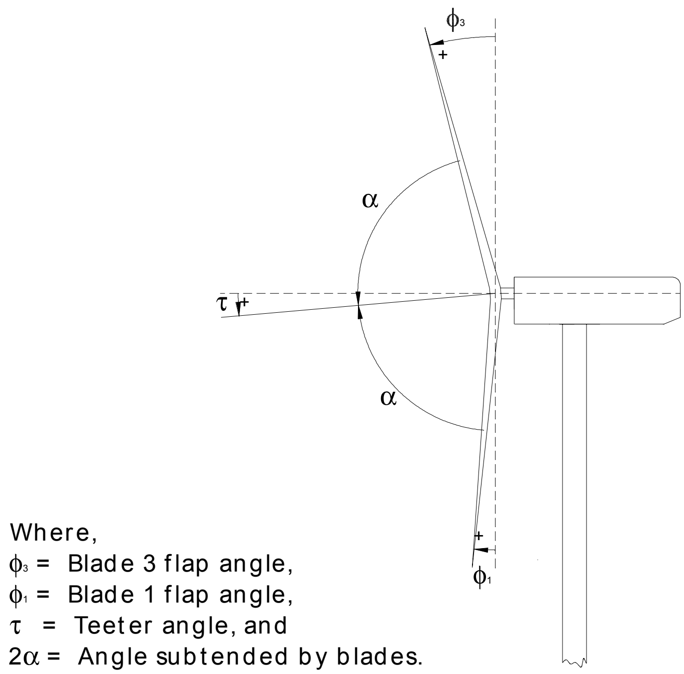


Figure 12. Blade flap angle convention

Generator power was monitored using an Ohio Semitronics, Inc. (OSI), power watt transducer during all phases of testing. A time code generator provided a signal to which all of the PCM streams were synchronized. These miscellaneous channels are listed in Table 9 below and fully described in Appendix B.

Table 9. Miscellaneous Transducers

Channel	Channel ID	Description	Units
251	B1FLAP	Digital Blade 1 Teeter Angle	deg
253	B1PITCH	Digital Blade 1 Pitch	deg
255	B3FLAP	Digital Blade 3 Teeter Angle	deg
257	B3PITCH	Digital Blade 3 Pitch	deg
332	GENPOW	Generator Power	kW
349	B3AZI	Blade 3 Azimuth Angle	deg
351	YAW	Yaw Angle	deg
353	DAY	Clock - Day	day
355	HOUR	Clock - Hour	hour
357	MINUTE	Clock - Minute	minute
359	SECOND	Clock - Second	second
361	MILLISEC	Clock - Millisecond	msec

Flow Visualization

Cameras

Two high-shutter-speed cameras were mounted in the rotating frame. A Panasonic camera with a Rainbow™ zoom lens and remote control iris and focus adjustments was mounted on the end of a lightweight, 3-m boom, which was attached to the hub. The boom was designed to be stiff with a system fundamental frequency exceeding 10 cycles per revolution (10 P), and the axes of the boom and camera were mass balanced about the axis of rotation. The camera angle was remotely adjustable to display various span locations on the blade. An additional high-shutter-speed video camera was mounted at the root of the instrumented blade to provide a view of the blade span. This camera pitched with the blade to provide a full-span picture of all the tufts at one time. The mass of this camera was included in the mass of the blades listed in Appendix A. Additional equipment, such as the data acquisition system, the PSC, and lighting for night testing, was also mounted on the hub.

Tufts

Flow visualization was achieved through the use of tufts attached to the surface of the blade. The tufts were made of thin, white, polyester thread measuring about 0.25 mm in diameter and 45 mm in length. A small drop of fast-drying glue held each of the tufts to the downwind (suction) side of the instrumented blade. The tufts extended from the leading edge to the trailing edge in 50.8-mm increments. The tufts were also spaced 50.8 mm in the span-wise direction. However, if the 50.8-mm radius of a tuft would interfere with any pressure tap, the tuft was omitted. Thus, the tip of a tuft could be as close as 6 mm to a tap or as far away as 50.8 mm. The diameter of the tufts was chosen to minimize the effects on the boundary layer yet maintain good visibility for the video camera. If the tufts were large relative to the boundary layer thickness, they could cause transition or premature separation. This effect is discussed in more detail by Rae and Pope (1984).

Lighting

Daylight tended to produce glare and reflections that interfered with video images. Thus, night testing was preferred. In order to collect data at night, four 100-W Halogen-IR™ bulbs and two 250-W Halogen-IR™ bulbs were mounted on the boom and were used for some campaigns. These bulbs operate at a color temperature of 2900 K and produce 2000 and 3370 lumens, respectively.

Data Acquisition and Reduction Systems

PCM System Hardware

In order to increase accuracy, simplify instrumentation, and reduce noise, digital and analog data signals are sampled and encoded into PCM streams as close to the transducer as possible. For this reason, three PCM streams originate in the instrumentation boxes mounted on the hub, and one PCM stream originates in the data shed at the base of the turbine. The rotor streams are conducted through slip rings and cables to the data shed, where all four streams are then decommutated and stored on optical disk.

A customized digital PCM-based hardware system for data acquisition was developed and tested throughout Phase I of the Unsteady Aerodynamic Experiment (Butterfield, Musial, and Simms 1992). The same hardware was used during Phase II, but upgrades were made for subsequent phases. The number of measured channels increased from 185 in Phase II to 207 in Phase V. All of the channels were sampled at 520.83 Hz and stored directly to optical disk. Copies of the optical disks and the processed engineering-unit files were recorded on compact discs for dissemination.

The PCM encoders convert conditioned analog input voltages into digital counts. The digital signals are also encoded into PCM streams. The digital conversion code limits the overall accuracy to 12-bit resolution for count values ranging from 0 to 4095. Therefore, quantizing errors are limited to 0.024% of full scale, and the peak signal-to-noise ratio (S/N) is 83 dB. Signal conditioning of the analog signals prior to PCM encoding allows the channels to use as much of the quantizing range as possible. Also, filtering the analog signals prior to PCM encoding reduces the potential for aliasing. The pressure signals were not filtered due to the filtering effect of the long pressure tap tubes. Also, it is extremely difficult to filter analog-multiplex signals.

The decoder boards are printed circuit boards mounted inside the chassis of a PC. The specifications are listed in Table 10, which is taken from Butterfield, Musial, and Simms (1992). Software that controls the decoder boards was written in C for DOS. Upon receiving a capture command, a direct memory access (DMA) controller moves decoded data from the PCM board to computer memory in variable buffer sizes from 0-64 kilobytes. Each word is tagged with its corresponding PCM board number, and custom software was developed to facilitate conversion of the PCM data to binary files.

Table 10. Phase II PCM Decoder Board Specifications

Bit Rate	1-800 Kbits/second
Input Streams	4 (only one processed at a time)
Input Polarity	Negative or positive
Input Resistance	> 10 Kohms
Codes	Bi-phase L, NRZ
Bit Sync Type	Phase-locked loop (PLL)
Input Data Format	8-12 bits/word, most significant bit (MSB) first
Words Per Frame	2-64 (including sync)
Sync Words Per Frame	1-3 (maximum 32 bits)

(Butterfield, Musial, and Simms 1992)

Calibration Procedures

The most desirable form of calibration is to apply a known load and measure the response with the instrumentation system, i.e., a full-path calibration. Several points provide data for linear interpolation, and the slope and offset values of a linear transducer can then be determined. This form of calibration is used for the pressure transducers, the strain gauges, and the load cells. However, it is not feasible for a number of instruments because manufacturer calibrations are required, as in the case of anemometers. In this situation, calibration coefficients are obtained through the manufacturer. The analog instruments output values in units of volts, but the data acquisition system converts all measurements into digital counts. The electronic path from the instrument output through the data acquisition system must be calibrated to convert manufacturer-specified calibration coefficients in units of volts to units of counts. Lastly, the digital position encoders must be oriented with a known position to obtain the offset while the slope is prescribed by the instrument. Detailed descriptions of the calibration procedures for each channel are included in Appendix B.

Calibrations of the pressure channels were performed in the manner described in Simms and Butterfield (1991) by using a motorized syringe to apply positive and negative pressure to all scanning transducers simultaneously over their full measurement range. This was done before and after each 10-minute campaign by remote control while the turbine was operating. Calibration coefficients were derived by performing a least-squares linear regression on each of the pressure channels referenced to the precision digital pressure transducer signal. In order to verify lack of zero-drift in the pressure transducers, comparisons between pre- and post-calibrations were made.

The strain gauges were also calibrated by applying a known load. A jig was attached to each blade to isolate loads in both flap and edge directions. Weights were used to apply a moment, which was measured by the strain gauges. A least-squares regression analysis provided slope calibration coefficients. The zero offsets were determined by positioning each blade in zero-load locations of the rotational cycle. This calibration was performed prior to each series of data collection, which lasted less than 1 month.

A custom jig was built to apply loads to load cells in series. One of the load cells is considered the calibration load cell, and the others are the teeter link load cell or the button force sensors used to measure teeter impact. The jig is loosened or tightened over the range of the load cell being calibrated. The calibration load cell provides the known load. Linear regression provides slope and offset coefficients. Prior to the spring 1998 collection, the load cells were calibrated on the ground prior to installing the hub on the turbine. The data acquisition system was used to obtain the load measurements, and only the length of cable from the load cell to the system differed from field application. Prior to the fall 1998 campaigns, the teeter damper force load cells were zeroed by teetering the rotor into zero-load positions and recording count values. The slope values for all load cells were maintained throughout Phase V.

For the other channels, it was impossible to perform full-path calibrations *in situ*. For example, the cup anemometers required a known wind velocity and were thus calibrated by the manufacturer in a wind tunnel. Manufacturer calibrations generally provide both slope and offset values. In some cases, for example the optical-position encoders, the offset was determined by placing the transducer in a known position and noting the associated count value. For analog transducers, once the slope and offset calibration coefficients were obtained from manufacturer specifications, an electronic path calibration was performed. Known reference voltages were inserted in place of the transducer signal in order to separately calibrate the system electronic path. These values were used to convert the manufacturer-supplied calibration coefficients to units of counts.

A database of resulting calibration coefficients was maintained and applied to raw data values to produce engineering unit data files. Because all of the measured channels were linear, only slope and offset calibration coefficients were applied.

These calibration procedures were established to ensure that all recorded data values were within the stated error limits. Uncertainty analysis results for selected measured channels used during Phase II are presented in Table 11. Total estimated uncertainty values listed in the table are expressed in engineering units, and represent random and bias error components. The uncertainty is also expressed in terms of percent full-scale error. Error analysis and calibration procedures specific to wind turbine field testing are described in McNiff and Simms (1992).

Table 11. Uncertainty Analysis Results for Selected Phase II Measured Channels

Measurement	Units	Measurement Range	Total Estimated Uncertainty	% Full-Scale Error
Pressures at 30% span	Pa	± 2970	±12	0.2
Pressures at 47% span	Pa	± 2970	± 18	0.3
Pressures at 63% span	Pa	± 8274	± 33	0.2
Pressures at 80% span	Pa	± 8274	± 50	0.3
Angle of Attack	deg	-22 to 40	± 1.0	1.6
Wind Velocity	m/s	0 to 37	± 0.5	1.4
Blade Pitch Angle	deg	-10 to 71	± 1.0	1.2
Blade Azimuth Angle	deg	0 to 360	± 1.0	2.8

PCM System Software

A diagram of the signal path from PCM streams to useable data, along with the possible viewing options is shown in Appendix B (Figure 51). It was possible to view a bar graph showing all channels within each of the four PCM streams. The count value of a user-selected channel was noted on the bottom of the screen. The most powerful real-time viewing program displayed nearly all measured channels on one screen. Each of the five pressure distributions, angles of attack, and dynamic pressures were displayed graphically in real time. Inflow conditions such as wind speed, vertical and horizontal wind shear, azimuth angle, yaw angle, and wind direction were displayed as well. A bar graph tracked power, root flap bending moment, damper load cells, and low-speed shaft torque. Other parameters such as time, pitch angles, Richardson number, and rotational speed appeared as text. This program could also be used to review recorded data at adjustable speeds. Time histories of user-selected channels could be displayed by selecting an averaging value. Each point average was updated graphically in real time. This software provided a means of determining inoperable channels quickly and easily. A variation of this program was used to combine video camera images with superimposed graphical and text data. The resulting integrated video and data image archives are stored on video tape.

The flowcharts presented in Appendix B (Figures 52 and 53) illustrate the process of creating the engineering-unit files which are stored on compact disc. Pressure calibrations were initiated with *psc.exe,* which controls the syringe in the PSC package. The resulting measurements were fit to a linear curve with the corresponding slope and offset values entered in the *prescal.hdr* file. A similar process was performed using the *gencal.exe* program to determine slope and offset values for the strain gauges, load cells, and electronic-path calibrations. All of the other calibration coefficients for anemometers, accelerometers, optical absolute position encoders, and the power transducer were determined using manufacturer specifications and/or single-point offset determination which were entered in the spreadsheet *calconst.xls*. The *buildhdr.exe* program converted the manufacturer-supplied calibration coefficients in units of volts to engineering units created by the electronic-path calibrations. Production of the *master.hdr* file resulted in one file containing all slope and offset values for each measured channel. This file, together with the recorded data file, (**.dat*), was input to the main processing program called *munch.exe*. This program requires additional input files that explain the pressure profiles (*cexp.prf*), the blade shape (*cexp.bsh*), the record format (*cexp.rft*), and the ID codes for the data channels (*chanid.txt*).

Three files were created by the *munch.exe* program: the updated header file, the engineering-unit file, and an archive file. The header file contained a description of each channel, calibration coefficients, and statistics for the 10-minute campaign (mean, standard deviation, maximum, record location of maximum, minimum, record location of minimum, and number of errors). An example of the header file is attached in Appendix B, p. 121. The engineering-unit file contained the time series of each channel converted from PCM code to engineering units. Additionally the time series of several derived channels such as normal and tangential force coefficients were included. An example of the format of the engineering-unit file appears in Appendix B, p. 122. The archive file consisted of a copy of the data file in the event of corruption or destruction. All of these files were stored on compact disc along with the calibration files and *munch.exe* input files.

While creating the engineering-unit file, a byte is attached to each record to indicate whether channels exceeded the measurement ranges. This "error byte" contains 8 bits representing each of the five span locations, the 4% chord and 36% chord span-wise distributed taps, and one bit for all other channels. If the bit is turned on, the maximum value of the transducer was exceeded for at least one of the channels associated with that bit. For instance, if the pressure at any tap at 30% span exceeds the transducer measurement range, the error bit representing the 30% span station is incremented.

In addition to the original high-rate (520.83 Hz) engineering-unit data files, various slower-rate averaged or filtered data files were subsequently produced. For example, once an engineering-unit file was created for each campaign, all of the channels were averaged over one complete rotation, or cycle, of the instrumented blade. A database of statistical values for each of these cycles for every channel was created. This process was performed for all campaigns and stored on compact disc. This database provided a means of identifying baseline performance and dynamic-stall occurrences. Additional post-processing software is described in Appendix B.

Derived Channels

Centrifugal Force Correction

The differential pressures between the blade surface pressure and the hub reference pressure were reduced by the centrifugal force acting on the column of air in the pressure tubing caused by rotation of the blade. This force was added to each measured pressure data value per Equations (3) and (4). Each of the probe pressures was also corrected in this manner.

$$P_{cor} = P_{meas} + P_{cent}\ , \tag{3}$$

$$P_{cent} = \frac{1}{2}\rho(r\omega)^2\ \text{, and} \tag{4}$$

$$\rho = 0.0034838 * \frac{P_{atm}}{T}\ \text{(Smithsonian Institution 1949);} \tag{5}$$

where
P_{cor} = differential pressure corrected for centrifugal force (Pa),
P_{meas} = pressure differential measured at blade-mounted transducer (Pa),
P_{cent} = centrifugal force correction (Pa),
ρ = air density (kg/m^3),
r = radial distance to surface pressure tap (m),
ω = rotor speed (rad/s),
P = atmospheric pressure (Pa), and
T = air temperature (K).

Dynamic Pressure

Assuming that the reference pressure is free stream static pressure, two measurements of dynamic pressure were obtained: probe dynamic pressure and stagnation point dynamic pressure. Note, however, that without application of the reference pressure correction, these values are offset from the dynamic pressure because the reference pressure for the pressure transducer was not free-stream static pressure.

The pressure measured with the 5-hole probes and corrected for centrifugal effects was one measure of dynamic pressure, and these channels are listed in Table 12. The difference between the inboard and outboard ports was normalized with the center port pressure after the centrifugal force correction was applied. The difference between the upper and lower ports was normalized similarly. The probe dynamic pressure was then extracted from the lookup table using these two numbers. An algorithm using a spherical coordinate system was developed to obtain the probe dynamic pressure measurement from the look-up table (Freeman and Robinson 1998).

The dynamic pressure was also estimated from the stagnation point pressure at each of the full-chord pressure tap locations as shown in Table 12. The pressure tap at each primary span location where the static pressure attains a maximum was considered to be the stagnation point, and the corresponding pressure at that location was used as the stagnation pressure. The resolution of the pressure taps on the lower surface was assumed to be sufficient to extract the maximum positive surface pressure, especially at lower angles of attack. According to Shipley et al. (1995), the stagnation point method is the preferred method of estimating dynamic pressure on the blade. This measurement of dynamic pressure was used to normalize each of the blade surface pressures and is thus referred to as the normalization pressure.

Table 12. Dynamic Pressure Measurements

Channel	Channel ID	Description	Units
822	QNORM30	Normalization Factor at 30% Span	Pa
828	QNORM47	Normalization Factor at 47% Span	Pa
834	QNORM63	Normalization Factor at 63% Span	Pa
840	QNORM80	Normalization Factor at 80% Span	Pa
846	QNORM95	Normalization Factor at 95% Span	Pa
852	5HP34P	5-hole 34% Pressure	Pa
855	5HP51P	5-hole 51% Pressure	Pa
858	5HP67P	5-hole 67% Pressure	Pa
861	5HP84P	5-hole 84% Pressure	Pa
864	5HP91P	5-hole 91% Pressure	Pa

Pressure Coefficients

Each of the corrected blade surface pressure values was normalized by the stagnation pressure at the corresponding span location as shown in Equation 6. These values were recorded in the engineering-unit files for each pressure tap.

$$C_p = \frac{P_{cor}}{Q_{stag}}; \qquad (6)$$

where
C_p = pressure coefficient, dimensionless,

P_{cor} = differential pressure corrected for centrifugal force (Pa), and
Q_{stag} = stagnation point dynamic pressure (corrected for centrifugal force) (Pa).

If a pressure tube was damaged, the nearest working tap was instrumented. Using this additional measurement, a value for the damaged tap was determined through either interpolation or extrapolation, depending on the location of the tap. These channels were noted as 'P(deriv)' in the header files to indicate derivation instead of actual measurement. The trailing edge taps at 63% span (P0163100) and 95% span (P0195100) were both damaged so the tap at 92% chord (P026392U, P029592U) on the upper surface was instrumented to provide an extrapolated value of the trailing edge tap. The intermediate tap pressure at 85% span, 36% chord (P118536U) was derived by interpolation of span-wise adjacent tap measurements.

Aerodynamic Force Coefficients

The pressure distributions for rotating-blade data were integrated to compute normal force coefficients (C_N) and tangent force coefficients (C_T), which represent the forces acting perpendicular and parallel to the airfoil chord, respectively. The average pressure between two adjacent taps was first projected onto the chord line, integrated to determine the C_N values, and then projected onto an axis orthogonal to the chord and integrated to compute C_T values. This procedure is described in detail by Rae and Pope (1984). Equations 7 and 8 give the integration procedure used to determine C_N and C_T. The x and y values begin at the trailing edge (x = 1), proceed forward over the upper surface of the blade, and then aft along the bottom surface, ending at the starting point, the trailing edge.

$$C_N = \sum_{i=1}^{\#oftaps} \left(\frac{C_{p_i} + C_{p_{i+1}}}{2} \right) \left(x_{i+1} - x_i \right), \text{ and} \tag{7}$$

$$C_T = \sum_{i=1}^{\#oftaps} \left(\frac{C_{p_i} + C_{p_{i+1}}}{2} \right) \left(y_{i+1} - y_i \right); \tag{8}$$

where,
C_p = normalized pressure coefficient
x_i = normalized distance along chord line from leading edge to i^{th} pressure tap
y_i = normalized distance from chord line along axis orthogonal to chord to i^{th} pressure tap.

In a similar integral procedure, pitching moment coefficients (C_M) were determined. The pitching moment represents the total moment about the pitch axis (1/4 chord) due to the normal and tangential forces at a pressure tap with the vertical or horizontal distance from the pitch axis as the moment arm. This equation follows:

$$C_M = -\sum_{i=1}^{\#oftaps} \left[\left(\frac{C_{p_i} + C_{p_{i+1}}}{2} \right) \left[\left(x_{i+1} - x_i \right) \left(\frac{x_{i+1} - x_i}{2} + x_i - 0.25 \right) + \left(y_{i+1} - y_i \right) \left(\frac{y_{i+1} - y_i}{2} + y_i \right) \right] \right]. \tag{9}$$

All other airfoil performance coefficients, such as lift (C_L), pressure drag (C_{Dp}), torque (C_{torque}), and thrust (C_{thrust}), were computed using the C_N and C_T values together with their reference angles. Torque and thrust coefficients were calculated as a function of blade pitch angle (β) and local twist angle (ϕ), both of which were easily measured. Lift and pressure drag coefficients, on the other hand, rely upon the angle of attack (α), which is not as easily acquired. For this reason, only torque and thrust coefficients were included in the recorded data, but the equations used to determine lift and pressure drag coefficients are shown below.

$$C_{Torque} = C_N \sin(\phi + \beta) + C_T \cos(\phi + \beta),$$
$$C_{Thrust} = C_N \cos(\phi + \beta) - C_T \sin(\phi + \beta),$$
$$C_L = C_N \cos(\alpha) + C_T \sin(\alpha), \text{ and}$$
$$C_{Dp} = -(C_N \sin(\alpha) - C_T \cos(\alpha)). \tag{10}$$

Torque and thrust coefficients were integrated along the span of the blade and multiplied by the number of blades (2) to provide a rough estimate of the total aerodynamic thrust and torque applied to the entire rotor. This integration divided the blade into panels that extend halfway between full-chord pressure tap locations. It was assumed that the pressure at the pressure tap location was applied evenly over the corresponding panel. The panel at the root began at 14.4% span and extended to halfway between the 30% and 47% span stations. The panel at the tip began halfway between the 80% and 95% stations and extended to the tip. There is no tip loss model applied. In highly yawed conditions, the assumption that each blade is enduring the same load is problematic. These estimates are provided primarily for the purpose of rough measurement cross-checking and estimating general trends in uniform flow conditions. Thrust is positive downwind and torque is positive in the direction of rotation. These derived channels appear in Table 13, and the equations follow:

$$EAEROTH = 2 * \sum_{n=1}^{5} C_{TH\,n} * QNORM_n * area_n \tag{11}$$

$$EAEROTQ = 2 * \sum_{n=1}^{5} C_{TQ_n} * QNORM_n * area_n * r_n \tag{12}$$

where ,
n = index for each panel,
QNORM = blade stagnation pressure at full-chord pressure tap location, Pa,
area = area of each trapezoidal panel, m^2,
r = radial location to full-chord pressure tap location along the blade span, m.

Table 13. Aerodynamic Force Coefficients

Channel	Channel ID	Description	Units
813	EAEROTH	Estimated aerodynamic thrust	N
814	EAEROTQ	Estimated aerodynamic torque	Nm
817	CN30	Normal Force at 30% Span	Cn
818	CT30	Tangent Force at 30% Span	Ct
819	CTH30	Thrust Coeff at 30% Span	Cth
820	CTQ30	Torque Coeff at 30% Span	Ctq
821	CM30	Pitch Moment Coeff at 30% Span	Cm
823	CN47	Normal Force at 47% Span	Cn
824	CT47	Tangent Force at 47% Span	Ct
825	CTH47	Thrust Coeff at 47% Span	Cth
826	CTQ47	Torque Coeff at 47% Span	Ctq
827	CM47	Pitch Moment Coeff at 47% Span	Cm
829	CN63	Normal Force at 63% Span	Cn
830	CT63	Tangent Force at 63% Span	Ct
831	CTH63	Thrust Coeff at 63% Span	Cth
832	CTQ63	Torque Coeff at 63% Span	Ctq
833	CM63	Pitch Moment Coeff at 63% Span	Cm
835	CN80	Normal Force at 80% Span	Cn
836	CT80	Tangent Force at 80% Span	Ct
837	CTH80	Thrust Coeff at 80% Span	Cth
838	CTQ80	Torque Coeff at 80% Span	Ctq
839	CM80	Pitch Moment Coeff at 80% Span	Cm
841	CN95	Normal Force at 95% Span	Cn
842	CT95	Tangent Force at 95% Span	Ct
843	CTH95	Thrust Coeff at 95% Span	Cth
844	CTQ95	Torque Coeff at 95% Span	Ctq
845	CM95	Pitch Moment Coeff at 95% Span	Cm

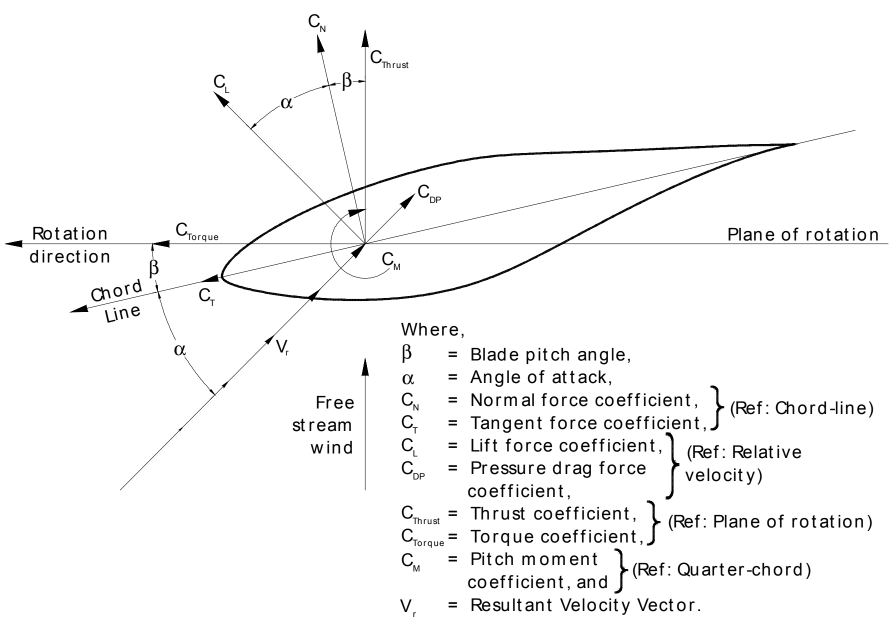


Figure 13. Aerodynamic force coefficient conventions

Flow Angles

The 5-hole probes measure the local flow angle and the spanwise flow angle as listed in Table 14. The angular values are extracted from tables based upon the neural network surfaces. The normalized difference between opposing ports in each 5-hole probe is used together with bi-linear interpolation to locate the resulting angle in each table. Tables exist for each probe for both the local flow angle and the spanwise flow angle.

The probe stalks were designed to be aligned with the chord and perpendicular with the pitch and twist axis. The probes were then attached to the stalk at a nominal 20° angle to place the probe in better alignment with the flow when the turbine is operating. The actual angle between the chord and the probe was measured at each span location. Table 14 contains these measured angles between each probe and the chord. The local flow angle measurement from the probe is not aligned with the full-chord pressure measurements introducing blade twist and rotational effects for which no correction is applied. The local flow angle recorded in these channels is relative to the chord of the blade at the radial location where the probe is mounted. In other words, the offset shown in Table 14 was added to the angle measured by each probe. The spanwise flow angle is positive outboard, and it is measured in the plane of the probe not the blade chord. No corrections for the 20° angle were made.

Table 14. Local Flow Angle Measurements (5-Hole Probe)

Channel	Channel ID	Description	Offset Angle	Units
853	5HP34A	5Hole 34% Local Flow Angle (Angle of Attack)	18.7	deg
856	5HP51A	5Hole 51% Local Flow Angle (Angle of Attack)	19.3	deg
859	5HP67A	5Hole 67% Local Flow Angle (Angle of Attack)	20.8	deg
862	5HP84A	5Hole 84% Local Flow Angle (Angle of Attack)	18.4	deg
865	5HP91A	5Hole 91% Local Flow Angle (Angle of Attack)	19.2	deg
854	5HP34F	5Hole 34% Spanwise Flow Angle		deg
857	5HP51F	5Hole 51% Spanwise Flow Angle		deg
860	5HP67F	5Hole 67% Spanwise Flow Angle		deg
863	5HP84F	5Hole 84% Spanwise Flow Angle		deg
866	5HP91F	5Hole 91% Spanwise Flow Angle		deg

Angle of Attack

During Phase II and Phase III tests, a flow-angle flag device was used to measure local flow angle. This assembly is shown in Figure 14. Wind tunnel tests were performed with the flag sensor mounted on a full-chord scale airfoil section in order to develop a correction for upwash and to determine the dynamic characteristics of the flag. The configuration and resulting data are explained in the Phase I report (Butterfield, Musial, and Simms 1992). The upwash correction derived from a polynomial fit of the wind tunnel test data was applied to the local flow angle measurements made with the 5-hole probes to arrive at the angle of attack. For measured local flow angles less than -10° and greater than 60°, linear relationships were used.

$$\alpha = 0.58090 * \alpha_m - 0.46470 \quad \text{for } \alpha_m < -10°;$$

$$\alpha = -(5.427E-5) * \alpha_m^{\ 3} + (6.713E-3) * \alpha_m^{\ 2} + (0.617) * \alpha_m - 0.8293;$$

$$\alpha = 0.93421 * \alpha_m - 7.4174 \quad \text{for } \alpha_m > 60°; \qquad (13)$$

where,

α = angle of attack (deg) and
α_m = local flow angle measurement (deg).

This upwash correction has proven satisfactory in determining aerodynamic performance (Simms et al. 1996) for measurements made with the flag sensor, but this application of the upwash correction to the 5-hole probe could be improved. The 5-hole probes measure a local flow angle 4% span outboard of the pressure tap locations (4% span inboard of the 95% pressure tap location) which are used to calculate aerodynamic force coefficients. Both the local flow angle measurement and the angle of attack were included in the engineering-unit files. Channels associated with angle of attack are listed in the table below.

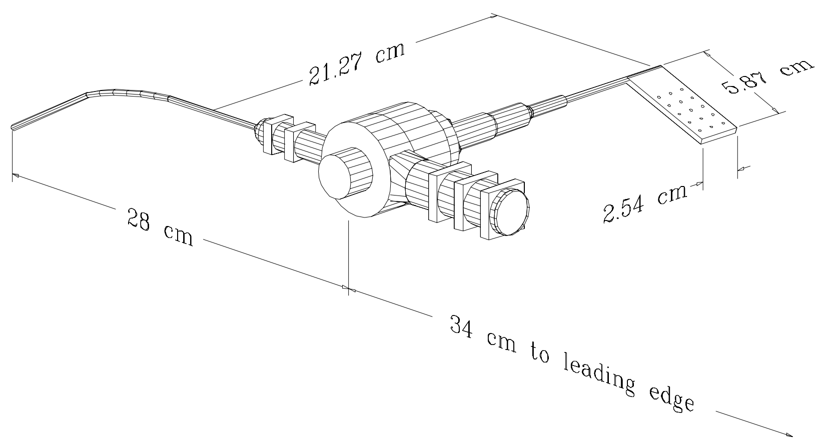


Figure 14. Local flow angle flag assembly.

Table 15. Upwash Corrected LFA Measurements

Channel	Channel ID	Description	Units
867	345HP	5HP 34% Span - Upwash Corrected	deg
868	515HP	5HP 51% Span - Upwash Corrected	deg
869	675HP	5HP 67% Span - Upwash Corrected	deg
870	845HP	5HP 84% Span - Upwash Corrected	deg
871	915HP	5HP 91% Span - Upwash Corrected	deg

Other Derived Channels

Yaw error describes the misalignment of the turbine with the prevailing wind. The channel representing yaw error included in the engineering-unit files was calculated by finding the difference between the sonic measured wind direction (LMSWD1) and the turbine angle (YAW). This value is then restricted to ± 180°.

$$yawerr = yaw - wind\ direction \tag{14}$$

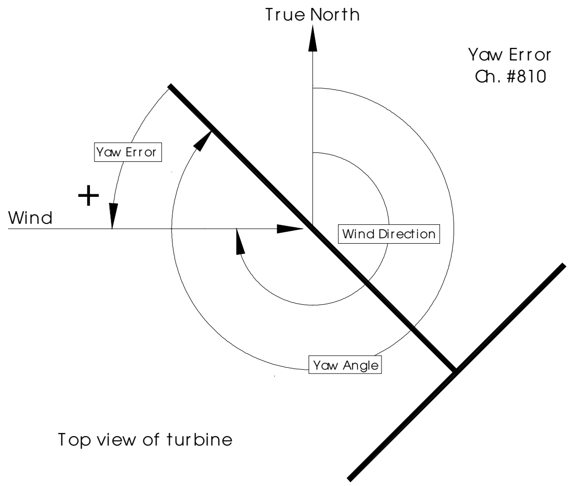


Figure 15. Yaw error angle convention.

The rotational speed of the rotor was determined as a running average. The blade azimuth position and the corresponding time for the record 150 steps prior to the current record are subtracted from the current blade azimuth and time. The output is in units of RPM.

Additionally, a cycle counting channel was incremented each time the instrumented blade completed a rotation.

The gradient Richardson number provides an indication of atmospheric stability based on temperature gradients and wind shear. This was calculated using the following equations on a sample-by-sample basis. This number is more appropriately calculated using time-averaged parameters. The data summary tables in Appendix D contain Richardson numbers calculated using 10-minute averaged wind speeds, temperature, and barometric pressure.

$$Ri = \frac{\left(\frac{9.8}{\Theta_m}\right)\left(\frac{\Delta\Theta}{\Delta Z}\right)}{\overline{V_{shear}}^2},\ \Theta = T\left(\frac{100{,}000}{P}\right)^{0.286},\ \overline{V}_{shear} = \frac{\sum_{n=1}^{N-1} \frac{WS_{n+1} - WS_n}{Z_{n+1} - Z_n}}{N-1}; \qquad (15)$$

where,
Ri = Richardson Number (dimensionless),
Θ_m = Average potential temperature between top of tower and bottom of tower (K),
$\Delta\Theta$ = potential temperature difference between top of tower and bottom of tower (K),
ΔZ = elevation difference between temperature measurements (m),
V_{shear} = Average vertical wind shear over ΔZ (m/s/m),
Θ = potential temperature (K),
T = measured, dry-bulb temperature (K),
P = barometric pressure (Pa),
N = number of wind speed measurements,
WS_n = wind speed (m/s), and
Z_n = elevation at n^{th} wind speed measurement (m).

A sonic anemometer was used to measure wind velocity and direction in the u, v, and w orthogonal component directions. These vector components were transformed into magnitude and direction during post-processing using vector relations.

The 16-bit Mensor signal was stored as two data channels during data collection. The post-processing software accommodated glitches that occurred with the channel containing the additional 4 bits. These two channels were converted into one engineering unit channel that provided the difference between the upwind free-stream static pressure and the reference pressure inside the instrumentation box.

Table 16. Miscellaneous Channels

Channel	Channel ID	Description	Units
810	YAWERR	Yaw Error	deg
811	RPM	Current RPM	rpm
812	CYCLECNT	Cycle Count	rev
815	MENSOR	Mensor	Pa
816	RICHN	Richardson Number	(none)
850	LMSWS1	Sonic #1 WS (horiz)	m/s
851	LMSWD1	Sonic #1 WD	deg

Reference Pressure Correction

Every pressure transducer was referenced to the pressure inside one of the instrumentation boxes. If this pressure is assumed to be free-stream static pressure, then the total pressure measurements made with the 5-hole probes are actually dynamic pressure measurements. For the same reason, the stagnation pressure on the blade is also a measurement of dynamic pressure. The dynamic pressure of the free stream can be estimated using the wind speed measurements from the cup anemometers and local air density derived from temperature and barometric pressure data. Comparison of the wind-speed-derived dynamic pressure and the pressure system measured dynamic pressures (neglecting the dynamic pressure due to rotational effects at each span location) showed a consistent offset. This offset has been attributed to the fact that the pressure inside the instrumentation box is not free-stream static pressure, as was assumed. Therefore, all of the pressure measurements must be corrected by subtracting the difference between the pressure in the box and the free stream static pressure.

The measured dynamic pressure on the blade that is stored in the data files includes the correction applied to account for the centrifugal force acting on the air in the reference pressure tube. By subtracting this amount, the result is the actual pressure measured by the transducer. This value was plotted versus the wind speed derived dynamic pressure for each of the five span locations. The data plotted were cycle-averaged values that were selected using limiting criteria on wind speed variation and yaw error angle variation over the cycle. All wind speed ranges and yaw error angle ranges were included. A linear fit was applied to the data representing each of the five span locations, and the slope values were averaged. The deviation from a slope of 1.0 provides a measure of the difference between the box pressure and the free stream static pressure. Table 17 lists the correction factors for parked-blade data and for rotating-blade data.

Table 17. Reference Pressure Correction Factors

Phase V	Correction factor
Parked blade	0.24
Rotating blade	0.32

The correction must be applied to all of the data on either a cycle-averaged or time-step basis by users of the data. The magnitude of the correction is determined using the blade stagnation pressure at 30% span and 47% span because these transducers have the highest resolution. First, the centrifugal force correction that was applied during post-processing is removed. Then the average measured dynamic pressure at the two span locations is calculated. The slope correction factor that was determined using data across all wind conditions is then applied, resulting in the magnitude of the pressure correction (Pa) that must be subtracted from all measured pressures at all span locations.

$$correction = factor * \frac{(Q_{stag\,30\%} - P_{cent\,30\%} + Q_{stag\,47\%} - P_{cent\,47\%})}{2}; \tag{16}$$

where,
Q_{stag} = stagnation point pressure at the 30% or 47% station (Pa),
P_{cent} = centrifugal force correction at the 30% or 47% station (Pa), and
factor = varies for rotating and non-rotating conditions.

An example of the calculation of the correction magnitude for rotating-blade data using the channel ID codes is shown below:

1. Remove centrifugal force correction from blade dynamic pressure at 30% span and 47% span.

$$Q_{30} = QNORM30 - \frac{1}{2}\left(\frac{BARO}{287.04*(LMT2M + 273.15)}\right)\left(0.3*5.023*RPM*\frac{\pi}{30}\right)^2$$

$$Q_{47} = QNORM47 - \frac{1}{2}\left(\frac{BARO}{287.04*(LMT2M + 273.15)}\right)\left(0.47*5.023*RPM*\frac{\pi}{30}\right)^2$$

2. Average the measured dynamic pressures.

$$Q_{ave} = \frac{Q_{30} + Q_{47}}{2}$$

3. Apply correction factor.

$$correction = 0.32 * Q_{ave}$$

4. Correct measured pressure coefficient at 30% span, leading edge.

$$P2230000_{corrected} = \frac{P2230000 * QNORM30 - correction}{QNORM30 - correction}$$

The pressure difference measured by the Mensor was intended to provide this correction. By subtracting the Mensor signal from the measured pressures prior to centrifugal force correction, a corrected dynamic pressure value similar to the correction above is obtained. However, this measured pressure difference does not provide a correlation of 1.0 between the measured dynamic pressures and the wind speed estimated dynamic pressure. Thus, the upwind probe is influenced by the rotor and is not positioned such that it can measure free-stream static pressure.

Conclusions

The two-bladed, teetered-rotor version of the Unsteady Aerodynamics Experiment has successfully provided data in the 3-D unsteady operating environment. Full-chord pressure tap distributions permit calculation of aerodynamic force coefficients and pressure distributions at five span locations. The use of 5-hole probes near each of the full-chord pressure tap stations provides local flow angle and spanwise flow angle measurements. Additional measurements provide inflow conditions, position information, and loads at the blade root, hub shaft, and low-speed shaft. This report provides the reader with detailed information regarding the type of instrumentation used and the mathematical manipulations of the data.

Appendix A

Phase V Turbine Parameters

Basic Machine Parameters

- Number of blades: 2
- Rotor diameter: 10.046 m
- Hub height: 17.03 m
- Type of rotor: teetered
- Rotational speed: 71.63 rpm synchronous speed
- Cut-in wind speed: 6 m/s (tests were run at lower speeds)
- Power regulation: stall
- Rated power: 19.8 kW
- Tilt: 1° (positive tilt indicates boom tip higher than upwind side of low-speed shaft; blade pitch angle was calibrated assuming 1° tilt)
- Cone angle: 3.4°
- Location of rotor: downwind
- Rotational direction: clockwise (viewed from downwind)
- Rotor overhang: 1.32 m (yaw-axis to apex of blade cone angle; teeter pin 0.074 m downwind of apex).
- No full-system modal test was performed on this turbine configuration.

Rotor

Geometry

- Blade cross section and planform: NREL S809 (constant chord, no taper, optimally twisted)
- Root extension: 0.723 m
- Blade pitch angle (manually set by turbine operator): -9°, -3°, 3°, 8°, and 12° (see each data file).
- Blade profile: NREL S809
- Blade chord: 0.4572 m at all span stations
- Blade twist: see Table 18.

Table 18. Blade Twist

Radius from Rotor Center (m)	Twist (°)
0.724	44.67
0.880	39.39
1.132	32.29
1.383	26.56
1.634	21.95
1.886	18.19
2.137	15.10
2.389	12.52
2.640	10.35
2.892	8.50
3.143	6.91
3.395	5.52
3.646	4.32
3.897	3.25
4.149	2.30
4.400	1.45
4.652	0.69
4.903	0.00

(Composite Engineering 1994)

- Blade thickness:
  - At 14.4% span: t = 43.0% chord (span refers to rotor center)
  - Between 14.4% and 25.0% span the thickness decreases linearly
  - At 25.0% span: t = 20.95% chord
  - Outboard of 25.0% span: t = 20.95% chord
- Airfoil distribution: Except for the root, the blade uses the S809 at all span locations. The airfoil coordinates are shown in Table 19. In the root sections the airfoil shape is altered by the enlarged spar. This enlargement is a virtually perfect circle (in cross section) at the root, which is centered at the quarter chord. The thickness of the spar area enlargement varies from this maximum at the root to a thickness that fits inside the airfoil profile at the 25% span (and outboard). In between the root and 25% span the spar area enlargement is flattened into consecutively thinner and thinner elliptic shapes, but each ellipse has a perimeter equal to the circumference of the base circle. Figure 16 illustrates the blade surface in the root region.

Table 19. Airfoil Profile Coordinates

Upper Surface		Lower Surface	
x/c	y/c	x/c	y/c
0.00037	0.00275	0.00140	-0.00498
0.00575	0.01166	0.00933	-0.01272
0.01626	0.02133	0.02321	-0.02162
0.03158	0.03136	0.04223	-0.03144
0.05147	0.04143	0.06579	-0.04199
0.07568	0.05132	0.09325	-0.05301
0.10390	0.06082	0.12397	-0.06408
0.13580	0.06972	0.15752	-0.07467
0.17103	0.07786	0.19362	-0.08447
0.20920	0.08505	0.23175	-0.09326
0.24987	0.09113	0.27129	-0.10060
0.29259	0.09594	0.31188	-0.10589
0.33689	0.09933	0.35328	-0.10866
0.38223	0.10109	0.39541	-0.10842
0.42809	0.10101	0.43832	-0.10484
0.47384	0.09843	0.48234	-0.09756
0.52005	0.09237	0.52837	-0.08697
0.56801	0.08356	0.57663	-0.07442
0.61747	0.07379	0.62649	-0.06112
0.66718	0.06403	0.67710	-0.04792
0.71606	0.05462	0.72752	-0.03558
0.76314	0.04578	0.77668	-0.02466
0.80756	0.03761	0.82348	-0.01559
0.84854	0.03017	0.86677	-0.00859
0.88537	0.02335	0.90545	-0.00370
0.91763	0.01694	0.93852	-0.00075
0.94523	0.01101	0.96509	0.00054
0.96799	0.00600	0.98446	0.00065
0.98528	0.00245	0.99612	0.00024
0.99623	0.00054	1.00000	0.00000
1.00000	0.00000	0.00000	0.00000

(Butterfield , Musial, and Simms 1992)

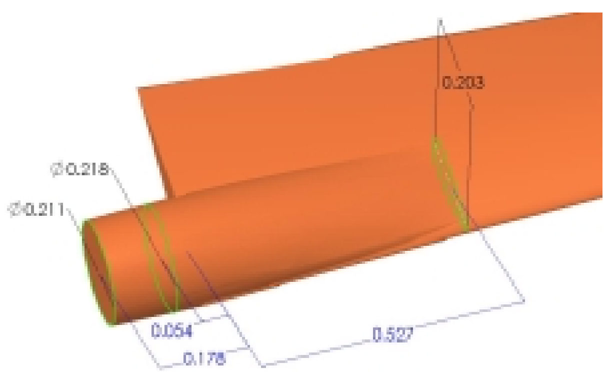


Figure 16. Blade root surface depiction (dimensions in meters)

Aerodynamics for S809 Airfoil

- Performance coefficients (α = angle of attack; C_l = lift coefficient, C_{dp} = pressure drag coefficient) obtained at the Colorado State University wind tunnel with a Reynolds number of 500,000 are shown in Table 20 (Butterfield, Musial, and Simms 1992; for additional wind tunnel measurements, see Somers 1997).

Table 20. Wind Tunnel Profile Coefficients

α	C_l	C_{dp}
-2.23	-6.00E-02	6.00E-03
-1.61E-01	1.56E-01	4.00E-03
1.84	3.69E-01	6.00E-03
3.88	5.71E-01	8.00E-03
5.89	7.55E-01	9.00E-03
7.89	8.60E-01	1.70E-02
8.95	8.87E-01	2.40E-02
9.91	8.69E-01	3.50E-02
10.9	8.68E-01	3.90E-02
12	8.94E-01	4.80E-02
12.9	9.38E-01	6.10E-02
14	9.29E-01	7.40E-02
14.9	9.08E-01	8.00E-02
16	9.12E-01	1.06E-01
17	6.55E-01	2.71E-01
18	5.88E-01	2.65E-01
19	5.87E-01	2.81E-01
20	5.97E-01	2.99E-01
22	6.03E-01	3.26E-01
24	6.47E-01	3.75E-01
26	6.83E-01	4.19E-01
28.1	7.45E-01	4.82E-01
30	8.24E-01	5.60E-01
35	1.05	8.17E-01
40	1.14	1.03
45	1.2	1.26
50	1.12	1.38
55	1.17	1.7
60	1.08	1.87
65	9.40E-01	1.98
70	8.57E-01	2.19
74.9	6.66E-01	2.17
79.9	4.72E-01	2.21
84.8	3.56E-01	2.32
89.9	1.42E-01	2.09

Structural Properties

- Rotor mass: 606.4 kg
- Pitch shaft, bull gear, instrumentation, bearings, nut, spacers: 38.6 kg (for one blade)
- Hub mass: 237.8 kg
- Boom, instrumentation enclosures, lights, and camera mass: 152.2 kg

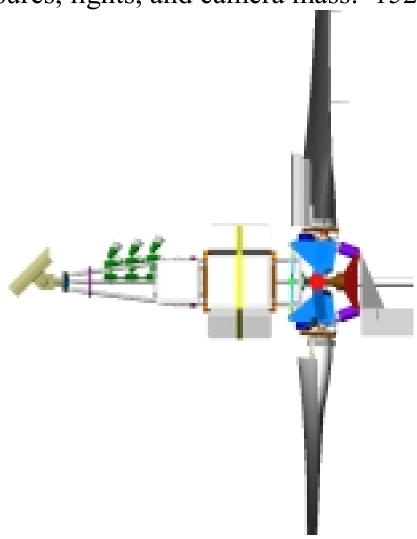


Figure 17. Hub-mounted instrumentation boxes, boom, and camera

- Blade material: Fiberglass/epoxy composite
- Blade mass (outside root; includes blade mounted camera):
  - Blade 1: 69.6 kg
  - Blade 3: 69.6 kg
- Blade center of gravity (from the center of rotation):
  - Blade 1: 2.004 m
  - Blade 3: 1.994 m
- Blade mass and stiffness distributions:
  - Estimates of mass and stiffness distributions were made by the blade manufacturer (Composite Engineering 1994). The pressure instrumentation and counterweights were included, as well as the root-mounted camera.

Table 21. Phase V, Twisted Blade, Structural Properties

Distance from Rotor Center (m)	Mass (kg/m)	Edgewise Stiffness (Nm^2)	Flapwise Stiffness (Nm^2)
5.029	9.32	46,953	365,070
4.526	9.25	46,953	387,600
4.023	10.22	65,974	436,440
3.520	11.19	84,468	512,420
3.018	12.06	105,560	583,420
2.515	12.95	123,480	650,900
2.012	13.49	149,420	737,010
1.509	16.92	232,180	997,640
1.006	46.09	710,230	1,332,800
0.749	45.18	1,302,400	1,556,800
0.508	30.14	2,320,700	2,322,100
0.402		473,517	473,517

- First edge-wise eigenfrequency:
  - Non-instrumented blade: 8.16 Hz, 0.84% damping
  - Instrumented blade: 7.97 Hz, 0.69% damping.
- First flap-wise eigenfrequency:
  - Non-instrumented blade: 4.94 Hz, 0.9% damping
  - Instrumented blade: 4.79 Hz, 0.95% damping.

Power Train

Layout

- The power train consists of the rotor mounted on a low-speed shaft coupled to a high-speed shaft via a gearbox. The high-speed shaft couples directly to an induction generator. The mechanical brake is positioned on the high-speed shaft.

Characteristics

- Power train inertia (low-speed shaft, gearbox, high-speed shaft, generator): 179 kg m^2
- Power train stiffness (low-speed shaft, gearbox, and high-speed shaft as a lumped parameter): $1.70 \cdot 10^5$ Nm/rad.
- Drive train frequency: 5.77 Hz
- Gearbox ratio: 25.13:1
- Gearbox inertia: Not available
- Gearbox stiffness: Not available
- Gearbox suspension stiffness: Not available
- Gearbox suspension damping: Not available
- High-speed shaft inertia: Not available
- High-speed shaft damping: 0.5% to 1.0%
- High-speed shaft stiffness: Not available
- Generator inertia: 143 kg m^2 w.r.t. low-speed shaft
- Generator slip: 1.59% at 20 kW

- Generator time constant: < 0.025 seconds (electro-mechanical time constant, for generator only)
- Power train efficiency:
  - Gearbox: 97% (from Grumman design documents)
  - Windage, couplings, main shaft bearings: 98% (from Grumman design documents)
  - Generator: The efficiency curve (in %) of the combined system (gearbox + generator) versus generator power (kW) is as follows:

    $$Eff = P_{gen}/((4.533223\cdot10^{-3})\cdot P_{gen}^{2} + (1.115023\cdot10^{0})\cdot P_{gen} + (1.500035\cdot10^{0}))*100.$$

    Thus, the efficiency is fairly constant at about 78%.
- Maximum brake torque: 115.24 Nm.

Tower

Description

- Basic description: two different diameter cylinders connected by a short conical section. The conical section base is 5.385 m above the ground. The conical section top is 6.300 m above the ground. The tower is further supported by four guy wires attached 11.91 m above the ground. The guy wires descend to the ground at an angle 44.3 degrees below horizontal. The ground anchors for the four wires are at the following compass directions from the tower axis: 90°, 180°, 270°, and 360°.

Characteristics

- Tower material: 9.525-mm Corten steel
- Tower height: 15.9 m
- Tower diameter(base): 0.4572 m
- Tower diameter(top): 0.4064 m
- Tower mass: 1481 kg
- Tower head mass: 1279 kg (hub and nacelle)
- Position of tower head c.g.: Not available
- Bending spring constant: 48,118 N/m
- Torsional stiffness: Not available
- Torsional damping: Not available
- Nacelle inertia: 1211 kg m^2
- First tower bending eigenfrequency (x): 5.49 Hz, 1.22% damping
- First tower bending eigenfrequency (y): 5.71 Hz, 1.49% damping
- First tower torsion eigenfrequency: Not available
- First tower/nacelle eigenfrequency (x): 1.95 Hz, 1.87% damping
- First tower/nacelle eigenfrequency (y): 1.94 Hz, 2.10% damping.

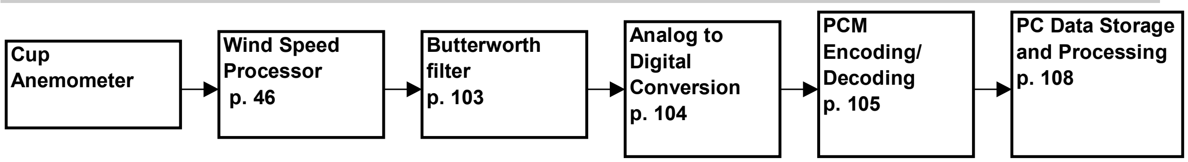
Appendix B

Instrumentation, Data Collection, and Data Processing for Phase V

Anemometers (Cup)

Channel	ID Code	Description
300	LMWS24M	Local met wind speed, 24.38 m
302	LMWS17M	Local met wind speed, 17.02 m (hub height)
304	LMWS10M	Local met wind speed, 10.06 m
306	LMWS2M	Local met wind speed, 2.4 m
308	NLMWS17M	North local met wind speed, 17.02 m (hub height)
314	SLMWS17M	South local met wind speed, 17.02 m (hub height)

Location	Met towers located 1.5D (15 m) upwind of turbine
Measurement type and units	Wind speed, m/s
Sensor description	Cup anemometer DC pulse output, photo chopper type Distance constant = 1.5 m Threshold = 0.45 m/s Accuracy = ±1% of true, certified at 6.70 m/s and 25.03 m/s Met One Instruments Model: 1564B (wind speed sensor), 170-41 (standard plastic cup set)



Location	Met rack in data shed
Range	0 to 50 m/s = 0 to 5 volts (Established with the following switch settings: S2 = 1,4,7; S3 = 5)
Resolution	10 m/s / volt
Output level	0-5 Vdc
Nonlinearity	±0.25% max
Calibration method	Manufacturer specifications (M1) and electronic path calibration (E1)
Description	Wind speed processor Met One Instruments Model: 49.03A (rack mount), 21.11 (processor), 48.11B (power supply)

Calibration Procedure

Manufacturer specifications - (M1)

1. A wind tunnel calibration was performed by Met One Instruments before installation of each anemometer. The correlation between the serial numbers of the cup assembly and the anemometer paired for calibration was maintained when installed in the field.
2. The wind speed processor is adjusted as follows:
   a. With mode switch set to LO, adjust voltage to 0 V ± 1 mV.
   b. With mode switch set to HI, adjust voltage to 3.810 V ± 1 mV (This value was specified by the manufacturer for a range of 0 m/s to 50 m/s.).
   c. Set mode switch to OP for normal operation.
3. Enter the slope (50 m/s / 5V) and the single-point offset (0 m/s / 0 V) in the appropriate columns of *calconst.xls* (see p. 119).

Electronic path calibration - (E1)

1. Modify *vbl.lst* so that the wind speed channels are listed at the top of the file. Set NV (number of variables) in the first line to the number of channels to be calibrated, and ensure that the correct PCM stream is specified in *gencal.cap* (all meteorological measurements are on PCM stream 3).
2. Connect the precision voltage generator to the processor output.
3. Run the *gc.bat* batch file which invokes both *gencal.exe* and *genfit.exe*. Collect samples for voltages ranging from 0 to 4.5 V in 0.5 V increments with two repetitions at each voltage level. The recorded input and output values are stored in the **.cao* input file. *Genfit.exe* computes slopes and offsets of the electronic path from the processor output to the computer in units of V/count and V, respectively. These values are stored in a temporary header file, **.hdr*. These slope and offset values are combined with the manufacturer-provided slope and offset stored in *calconst.xls* during the *buildhdr.bat* process to obtain units of engineering unit/count and counts, respectively.

Calibration frequency

The anemometers were calibrated prior to each series of data collection or upon replacement due to cup damage. Processors were adjusted prior to each series of data collection which lasted 1 month at most. On occasion, the processors were adjusted during a series of data collection.

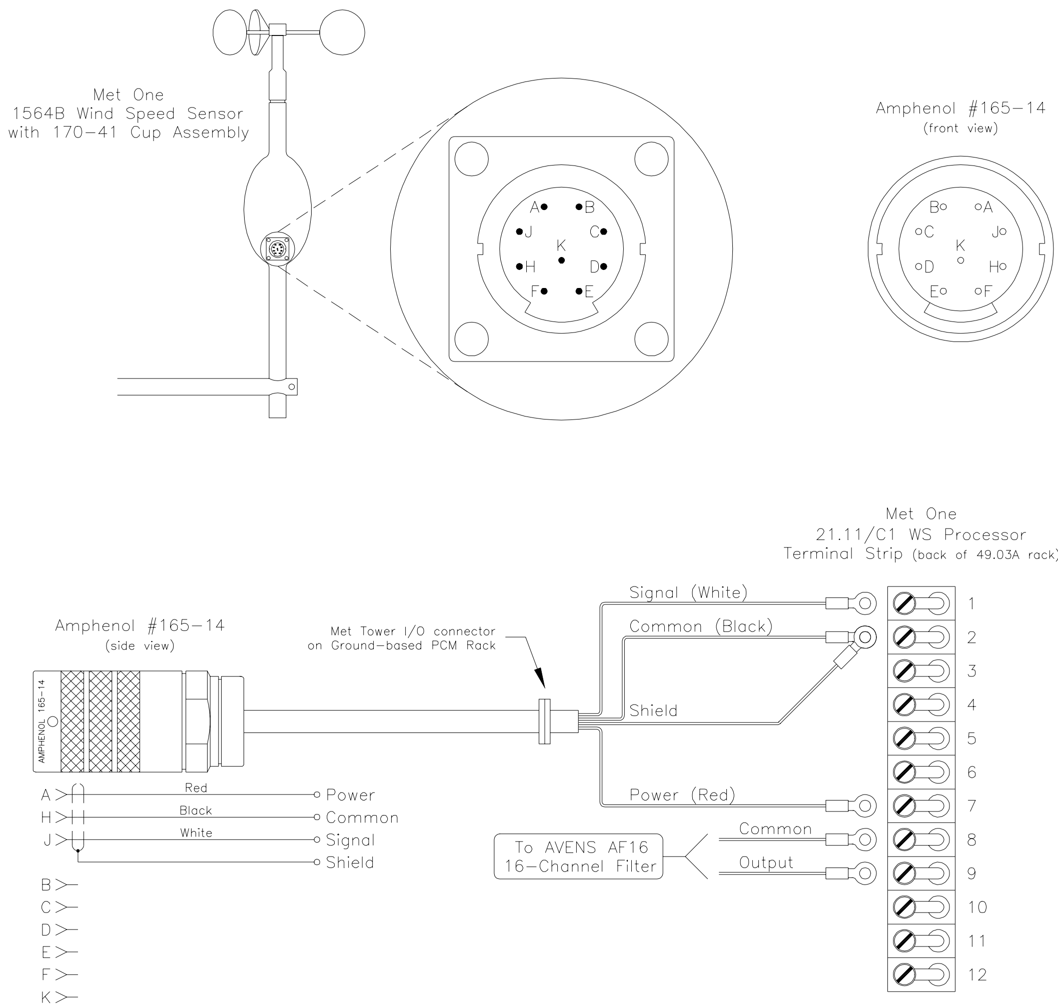
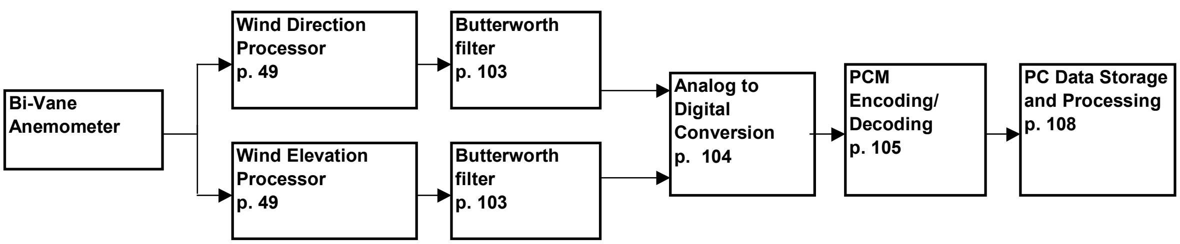


Figure 18. Cup anemometer wiring diagram

Channel	ID Code	Description
310	NLMWD17M	North local met wind direction, 17.02 m (hub height)
312	NLMWE17M	North local met wind elevation angle, 17.02 m (hub height)
316	SLMWD17M	South local met wind direction, 17.02 m (hub height)
318	SLMWE17M	South local met wind elevation angle, 17.02 m (hub height)

Location	North and South met towers located 1.5D (15 m) upwind of turbine
Measurement type and units	Wind direction and wind elevation angles, degrees
Sensor description	Bi-vane anemometer Distance constant = 1m (both wind direction and elevation) Threshold = 0.45 m/s (both wind direction and elevation) Accuracy = ±2° (both wind direction and elevation) Met One Instruments Model: 1585



Wind Direction Processor

Channel	ID Code	Description
310	NLMWD17M	North local met wind direction, 17.02 m (hub height)
316	SLMWD17M	South local met wind direction, 17.02 m (hub height)

Location	Met rack in data shed
Range	0° to 360° = 0 V to 5 V
Resolution	72°/volt
Calibration method	Manufacturer specifications (M2), single-point offset determination (S1), and electronic path calibration (E1)
Output level	0-5 Vdc
Linearity	±0.1% max
Description	Wind direction processor Met One Instruments Model: 49.03A (rack mount), 21.21 (processor), 48.11B (power supply)

Calibration Procedure

Manufacturer specifications - (M2)

1. The bi-vane anemometers were calibrated by Met One Instruments according to manufacturer specifications before installation.
2. The wind direction processor is adjusted as follows:
   a. With mode switch set to LO, adjust voltage to 0 V ± 1 mV.
   b. With mode switch set to HI, adjust voltage to 5 V ± 1 mV.
   c. Set mode switch to OP for normal operation.
3. Enter the slope (360°/5V) in the slope column of *calconst.xls*

Single point offset determination - (S1) - (This is a two-person operation requiring one person in the man-lift to position the vanes and one person on the ground to record the voltages.)

1. Man-lift person notifies ground person which transducer is to be calibrated and aligns the vane by eye with the North met tower (292° true north).
2. The ground person uses the voltmeter to record the vane position. The average voltage reading is inserted in the single-point offset column of *calconst.xls*.

Electronic path calibration - (E1)

1. Modify *vbl.lst* so that the wind direction channels are listed at the top of the file. Set NV (number of variables) in the first line to the number of channels to be calibrated, and ensure that the correct PCM stream is specified in *gencal.cap* (all meteorological measurements are on PCM stream 3).
2. Connect the precision voltage generator to the processor output.
3. Run the *gc.bat* batch file which invokes both *gencal.exe* and *genfit.exe*. Collect samples for voltages ranging from 0 to 4.5 V in 0.5 V increments with two repetitions at each voltage level. The recorded input and output values are stored in the **.cao* input file. *Genfit.exe*

computes slopes and offsets of the electronic path from the processor output to the computer in units of V/count and V, respectively. These values are stored in a temporary header file, **.hdr*. These slope and offset values are combined with the manufacturer-provided slope and offset stored in *calconst.xls* during the *buildhdr.bat* process to obtain units of engineering unit/count and counts, respectively.

Calibration frequency

Amplifier adjustment, offset determination, and electronic path calibrations were performed prior to each series of data collection, which lasted less than 1 month. On occasion, the processors were adjusted during data collection.

Wind Elevation Processor

Channel	ID Code	Description
312	NLMWE17M	North local met wind elevation angle, 17.02 m (hub height)
318	SLMWE17M	South local met wind elevation angle, 17.02 m (hub height)

Location	Met rack in data shed
Range	-60° to 60° (+ indicates ascending air)
Resolution	24°/volt (nominal)
Calibration method	Manufacturer specifications (M3), single-point offset determination (S2), and electronic path calibration (E1)
Output level	0-5 Vdc
Linearity	±0.1% max
Sensitivity	4.16 mV/Hz nominal
Span range	±25% nominal
Description	Wind elevation processor Met One Instruments Model: 49.03A (rack mount), 21.24 (processor), 48.11B (power supply)

Calibration Procedure

Manufacturer specifications - (M3)

1. The bi-vane anemometers were calibrated by Met One Instruments according to manufacturer specifications before installation.
2. The wind elevation processor is adjusted as follows:
    a. Determine LO and HI voltages using sensitivity (SEN [Hz/°]) provided by manufacturer and the full-scale elevation angle (FS = 60°) in the following formulae:
    $$ELO = 2.5 * (SEN * FS - 600)/(SEN * FS),$$
    $$EHI = 2.5 * (SEN * FS + 600)/(SEN * FS).$$
    b. With mode switch set to LO, adjust voltage to ELO ± 1 mV.
    c. With mode switch set to HI, adjust voltage to EHI ± 1 mV.
    d. Set mode switch to OP for normal operation.
3. Enter the slope (24°/volt) in the appropriate column of *calconst.xls*. The values used during Phases III and IV were determined in an unknown manner, but both bi-vane slopes were within 0.003°/volt of 24 °/volt.

Single point offset determination - (S2) - (This is a two-person operation requiring one person in the man-lift to position the vanes and one person on the ground to operate the computer.)

1. Man-lift person notifies ground person which transducer is to be calibrated and, using an Angle-star, positions the vane at 0°.
2. The ground person uses the voltmeter to record the vane position. The average voltage value is inserted in the appropriate column of *calconst.xls*.

Electronic path calibration - (E1)

1. Modify *vbl.lst* so that the wind elevation channels are listed at the top of the file. Set NV (number of variables) in the first line to the number of channels to be calibrated, and ensure that the correct PCM stream is specified in *gencal.cap* (all meteorological measurements are on PCM stream 3).
2. Connect the precision voltage generator to the processor output.
3. Run the *gc.bat* batch file which invokes both *gencal.exe* and *genfit.exe*. Collect samples for voltages ranging from 0 to 4.5 V in 0.5 V increments with two repetitions at each voltage level. The recorded input and output values are stored in the **.cao* input file. *Genfit.exe* computes slopes and offsets of the electronic path from the processor output to the computer in units of V/count and V, respectively. These values are stored in a temporary header file, **.hdr*. These slope and offset values are combined with the manufacturer-provided slope and offset stored in *calconst.xls* during the *buildhdr.bat* process to obtain units of engineering unit/count and counts, respectively.

Calibration frequency

Amplifier adjustment, offset determination, and electronic path calibrations were performed prior to each series of data collection which lasted less than 1 month. On occasion, the processors were adjusted during data collection.

S/N 055 Sensitivity = 12.75 Hz/deg, ELO = 0.539V, EHI = 4.461V (south met tower)
S/N 056 Sensitivity = 12.24 Hz/deg, ELO = 0.458V, EHI = 4.542V (north met tower)

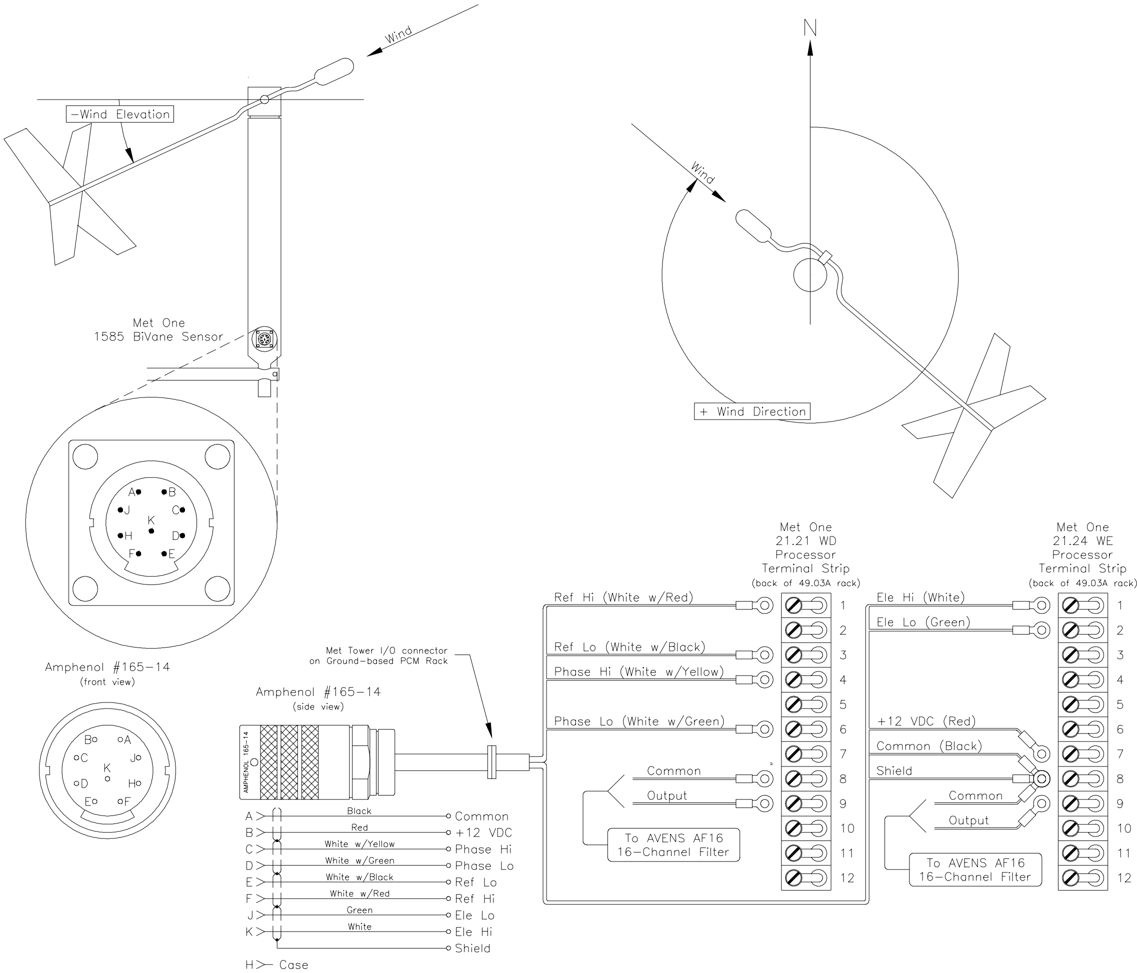
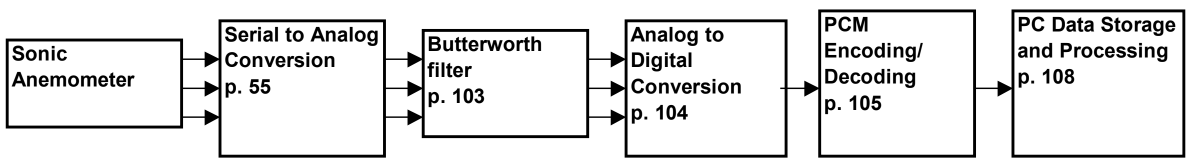


Figure 19. Bi-vane anemometer wiring diagram

Channel	ID Code	Description
326	LMSU17M	Local met sonic channel U, 17.02 m (hub height)
328	LMSV17M	Local met sonic channel V, 17.02 m (hub height)
330	LMSW17M	Local met sonic channel W, 17.02 m (hub height)

Location	Local met tower located 1.5D (15 m) upwind of turbine
Measurement type and units	3-D, orthogonal components of wind speed and direction, m/s
Sensor description	3-axis sonic anemometer Accuracy Wind speed, ±1% or ±0.05 m/s Wind direction, ±0.1° Temperature, ± 1% (not recorded) Applied Technologies, Inc. Model: SWS-211/3K



Note: Each of the three wind velocity components is contained in the PCM streams and recorded. Wind speed and direction are determined using these components during post-processing. The sonic's determination of wind speed, wind direction, and temperature is not used.

Sonic Serial to Analog Converter

Channel	ID Code	Description
326	LMSU17M	Local met sonic channel U, 17.02 m (hub height)
328	LMSV17M	Local met sonic channel V, 17.02 m (hub height)
330	LMSW17M	Local met sonic channel W, 17.02 m (hub height)

Location	Met rack in data shed
Range	±50 m/s at ±5 V (U,V); ±15 m/s at ±5 V (W)
Resolution	10 m/s / Volt (U,V); 3 m/s / Volt (W)
Calibration method	Manufacturer specifications (M4) and electronic path calibration (E1)
Input signal	Serial RS-232C
Output signal	±5 Vdc
Description	Serial to analog converter Applied Technologies, Inc. Model: SA-4

Calibration Procedure

Manufacturer specifications - (M4)

1. A calibration was performed by Applied Technologies before installation of the anemometer.
2. Enter the slope (50 m/s / 5 V for U and V; 15 m/s / 5 V for W) and the offset (0 m/s / 0 V for U, V, and W) in the appropriate columns of *calconst.xls*.
3. Transducer calibration
    a. Place zero-air chamber over axis to be calibrated. (Note: Ideally, this should be done in a controlled environment. Radiation from the sun can heat the inside of the chamber faster than the calibration is performed. If this is done outside, a cloudy day is preferable, and the ambient temperature must be greater than 0°C.)
    b. Enter the appropriate number in the “DATA ENTRY” thumbwheel. (U = 01, V = 02, W = 03)
    c. Press the “CALIBRATION” switch and enter the ambient air temperature (within ±1°C) once the “TEMP” light is illuminated. Depress the “CALIBRATION” switch once the temperature is entered.
    d. The “TEST” light will blink twice and the new transducer calibration is complete.

Electronic path calibration - (E1)

1. Modify *vbl.lst* so that the sonic channels are listed at the top of the file. Set NV (number of variables) in the first line to the number of channels to be calibrated, and ensure that the correct PCM stream is specified in *gencal.cap* (all meteorological channels are on PCM stream 3).
2. Connect the precision voltage generator to the processor output.
3. Run the *gc.bat* batch file which invokes both *gencal.exe* and *genfit.exe*. Collect samples for voltages ranging from –4.5 to 4.5 V in 1-V increments with two repetitions at each voltage level. The recorded input and output values are stored in the **.cao* input file. *Genfit.exe*

computes slopes and offsets of the electronic path from the processor output to the computer in units of V/count and V, respectively. These values are stored in a temporary header file, *.*hdr*. These slope and offset values are combined with the manufacturer-provided slope and offset stored in *calconst.xls* during the *buildhdr.bat* process to obtain units of engineering unit/count and counts, respectively.

Calibration frequency

The transducers were calibrated and an electronic path calibration was performed prior to each series of data collection which lasted less than 1 month.

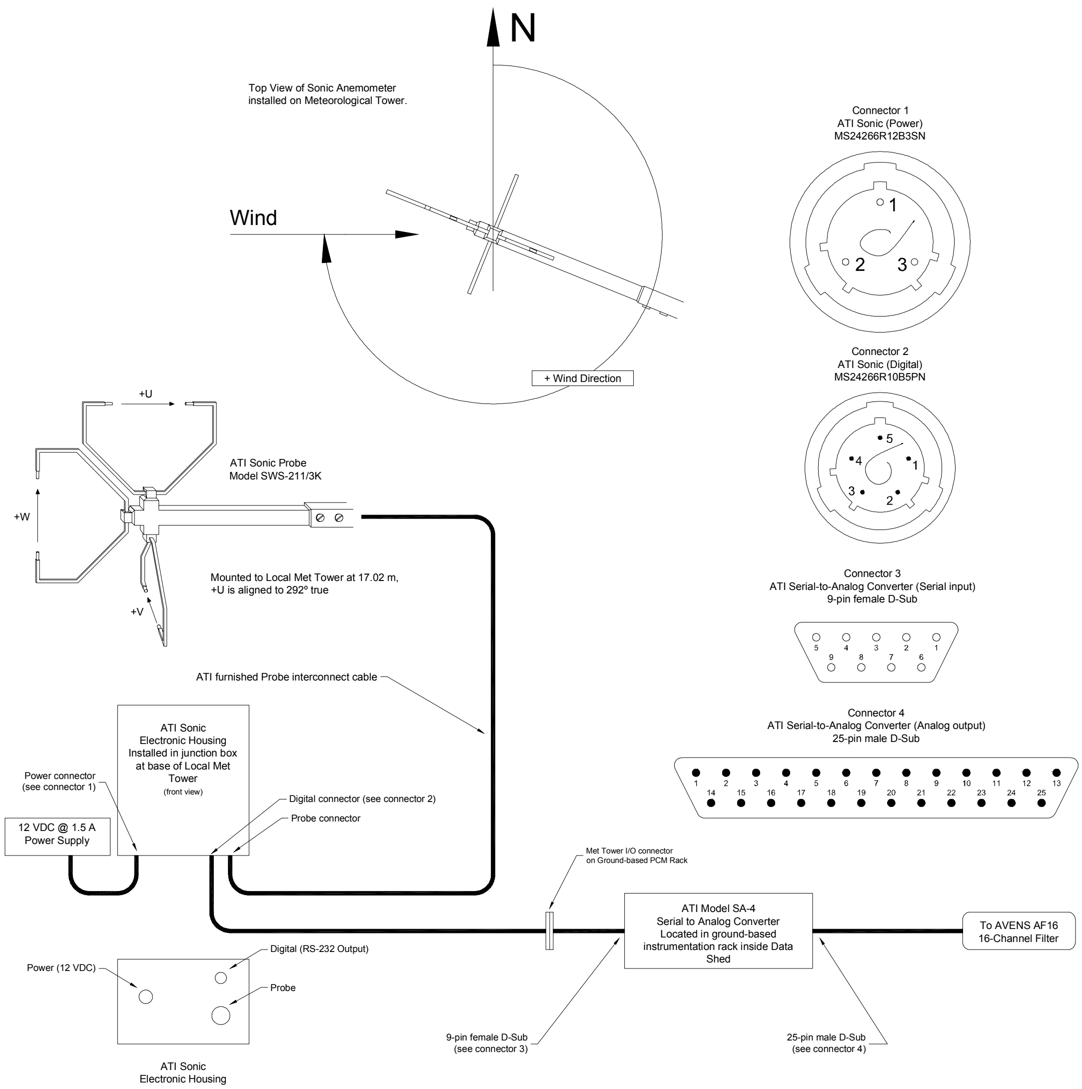
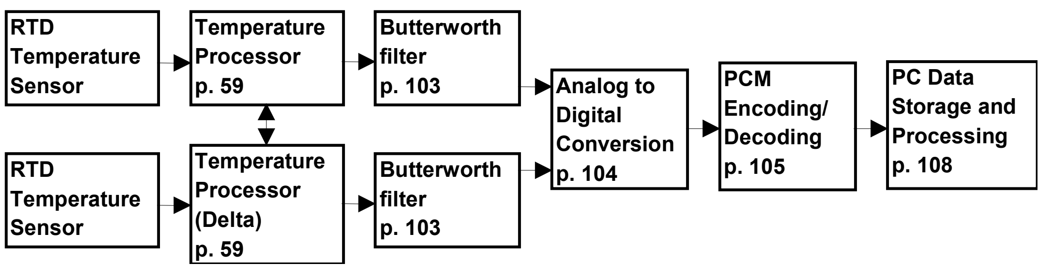


Figure 20. Sonic anemometer wiring diagram

Temperature (Ambient)

Channel	ID Code	Description
320	LMT2M	Local met temperature 2.4 m
322	LMDT	Local met Δ temperature, 24.48 m - 2.4 m

Location	Local met tower located 1.5D (15 m) upwind of turbine
Measurement type and units	Ambient temperature or delta temperature, °C
Sensor description	Platinum resistance element nominally 80Ω - 120 Ω for -50°C to 50°C R_o = 100±0.1Ω at 0°C Time constant < 10 seconds Met One Instruments Model: T-200 (sensor), 327C (aspirated radiation shield)

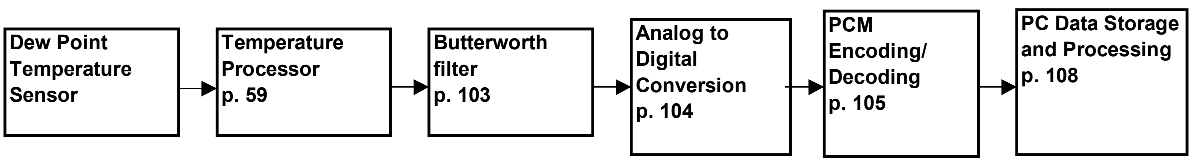


Note: Sensor is mounted in an aspirated radiation shield. If the aspirating fan malfunctions, a light on the met rack is illuminated, an audible alarm sounds, and data collection is halted.

Temperature (Dew Point)

Channel	ID Code	Description
324	LMDP2M	Local met dew point 2.4 m

Location	Local met tower located 1.5D (15 m) upwind of turbine
Measurement type and units	Dew-point temperature, °C
Sensor description	Dew-point temperature sensor DP systematic error = ±0.75°C DP random error = ±0.50°C Met One Instruments Model: DP200B (sensor), 327C (aspirated radiation shield)



Note: Sensor is mounted in an aspirated radiation shield. If the aspirating fan malfunctions, a light on the met rack is illuminated, an audible alarm sounds, and data collection is halted.

Channel	ID Code	Description
320	LMT2M	Local met temperature 2.4 m
322	LMDT	Local met Δ temperature, 24.48 m - 2.4 m
324	LMDP2M	Local met dewpoint 2.4 m

Location	Met rack in data shed
Range	-50°C to 50°C (ambient and dew point) -8°F to 12°F (delta)
Resolution	20 °C / volt (ambient and dew point) 2.22°C / volt (delta)
Calibration method	Manufacturer specifications (M5) and electronic path calibration (E1)
Output level	0-5 Vdc
Accuracy	Maximum error of ±0.1°C over specified processor operating temperature
Description	Platinum RTD processor (range specified by customer) Met One Instruments Model: 49.03A (rack mount), 21.32/21.43 (processor), 48.11B (power supply)

Amplifier calibration voltage calculation

1. Manufacturer calibration of RTD sensor yields values for R_o and α. Customer data sheet accompanying processor contains values for R_2 (LO) and R_3 (HI).
2. The values for EHI and ELO are determined for a specific sensor/processor pair using the following formulae:

$$TCAL = \frac{A-(A^2-B)^{0.5}}{1.1751E-6}$$

$$A = \alpha + 0.000058755$$

$$B = 2.3502E-6\frac{R-R_o}{R_o}$$

where, R is R_2 for determination of ELO and R_3 for determination of EHI.

3. The voltage is then determined using the following formula:

$$ECAL = 5\frac{TC-TLO}{THI-TLO}$$

where THI and TLO describe the temperature range specified when ordering the processor. TC = TCAL for absolute temperature modules. For delta temperature modules, both modules are calibrated separately, and the voltage is determined using TC = TCAL2 - TCAL1 where TCAL2 represents the delta temperature module and TCAL1 represents the absolute-temperature module. When calibrating dew-point temperature modules, if THI and TLO represent dew-point temperatures, the TCAL value must be converted to dew point using the following formula:

$$DPCAL = 0.68434 * TCAL - 23.88 .$$

Then the voltage is determined using TC = DPCAL, THI = DPHI, and TLO = DPLO.

Here are typical values not corrected for variations in processor and sensor. This results in a probable error of ±0.1°C and a worst case error of ±0.3°C for the temperature and dew-point measurements. For delta temperature, the error is doubled. It is recommended that the corrections specific to processor and sensor be used to restrict the error to ±0.05°C. These typical values were used to calibrate the processors for the Phase V, spring 1998 data collection because the manufacturer-supplied parameters were unavailable.

Temperature	EHI = 4.819V, ELO = 2.500V
Delta T	EHI = 4.338V, ELO = 2.000V
Dew point	EHI = 4.445V, ELO = 1.306V

New processors for temperature and delta temperature were obtained for the fall 1998 series of data collection. The calibration voltages resulting from the manufacturer-supplied values are listed below.

Temperature	EHI = 4.825V, ELO = 2.501V
Delta T	EHI = 4.339V, ELO = 1.997V

Calibration Procedures

Manufacturer specifications - (M5)

1. The RTD sensors and the dew-point sensor were calibrated by Met One Instruments before installation.
2. Using the calibration voltages determined above, the temperature processors are adjusted as follows:
    a. For each processor set the mode switch to LO, and adjust voltage to ELO ± 2 mV. Set the mode switch to HI, and adjust voltage to EHI ± 2 mV.
    b. For the delta temperature processor offset, set the mode switch of the delta temperature processor and of the ambient temperature processor to LO. Determine the ΔT offset using the TC values from step 3. Compute the ΔT offset output for this ΔT offset temperature.

    $$Voffout = 5\left(\frac{\Delta Toffset - \Delta TLO}{\Delta THI - \Delta TLO}\right)$$

    Adjust the zero voltage to the calculated offset voltage.

    c. Set mode switch to OP for normal operation.
3. Enter the slopes (20°C/V for ambient temperature and dew point, 2.222222°C/V for delta temperature) and offsets (2.5°C for ambient temperature and dew point, 2°C for delta temperature) in the appropriate columns of *calconst.xls*.

Electronic path calibration - (E1)

1. Modify *vbl.lst* so that the temperature channels are listed at the top of the file. Set NV (number of variables) in the first line to the number of channels to be calibrated, and ensure that the correct PCM stream is specified in *gencal.cap* (all meteorological channels are on PCM stream 3).
2. Connect the precision voltage generator to the processor output.
3. Run the *gc.bat* batch file which invokes both *gencal.exe* and *genfit.exe*. Collect samples for voltages ranging from 0 to 4.5 V in 0.5 V increments with two repetitions at each voltage level. The recorded input and output values are stored in the **.cao* input file. *Genfit.exe*

computes slopes and offsets of the electronic path from the processor output to the computer in units of V/count and V, respectively. These values are stored in a temporary header file, *.hdr*. These slope and offset values are combined with the manufacturer-provided slope and offset stored in *calconst.xls* during the *buildhdr.bat* process to obtain units of engineering unit/count and counts, respectively.

Calibration frequency

The RTD sensors were calibrated by the manufacturer prior to Phase V, spring 1998 data collection. New RTD sensors and processors were installed prior to the fall 1998 series of data collection. Amplifier adjustment, offset determination, and electronic path calibrations were performed prior to each series of data collection, which lasted less than 1 month. On occasion, the processors were adjusted during data collection.

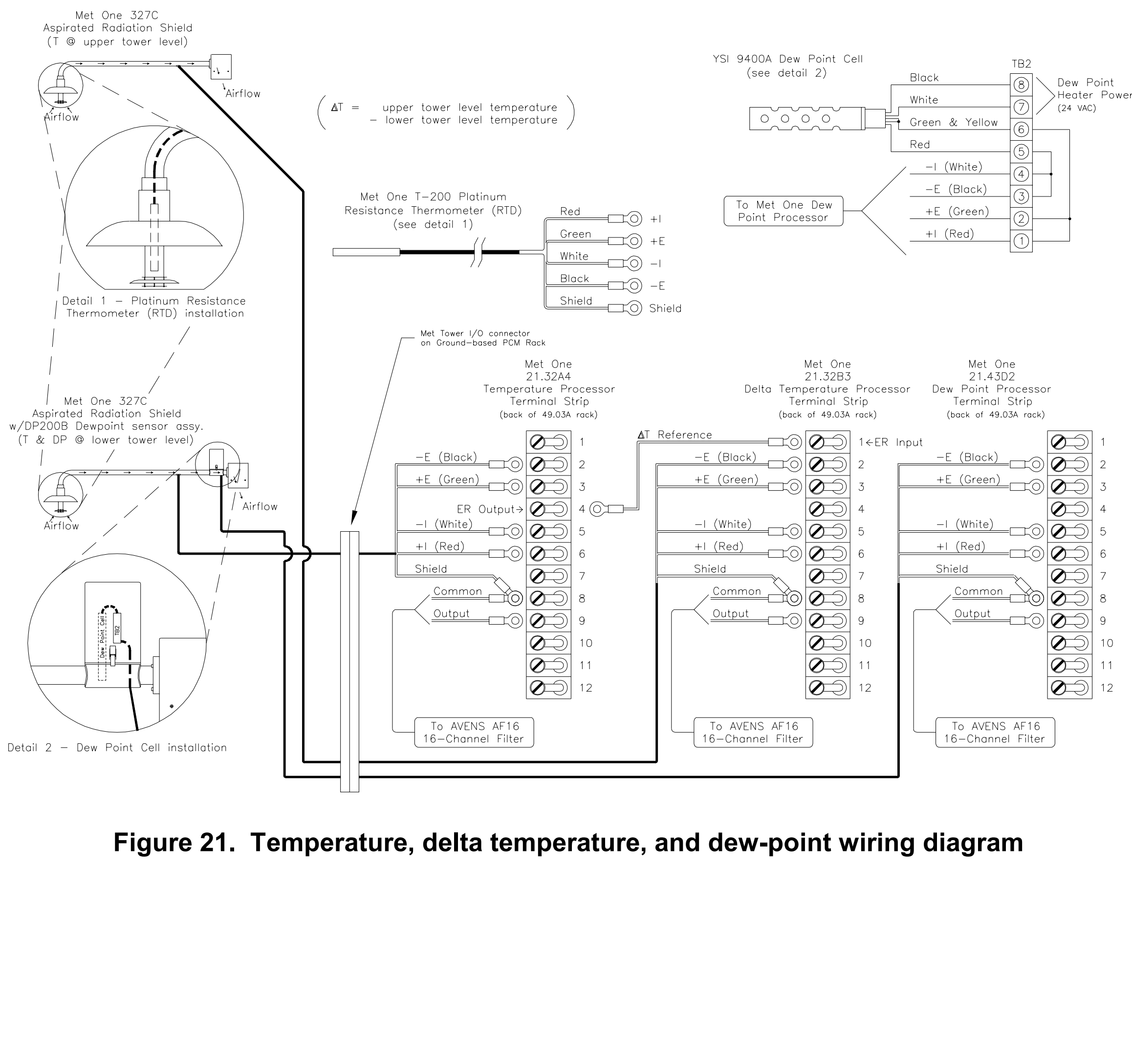
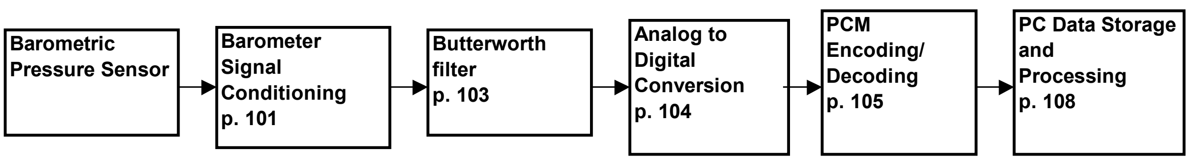


Figure 21. Temperature, delta temperature, and dew-point wiring diagram

Barometric Pressure

Channel	ID Code	Description
334	BARO	Barometric pressure

Location	Met rack inside data shed
Measurement type and units	Ambient air pressure, Pa
Excitation	15 Vdc
Range	74000 to 100000 Pa = 0 to 5V
Resolution	5200 Pa/V
Calibration method	Manufacturer specifications (M6) and electronic path calibration (E1)
Sensor description	Ambient air pressure transducer Atmospheric Instrumentation Research, Inc. Model: AIR-AB-2AX



Calibration Procedure

Manufacturer specifications - (M6)

1. A calibration was performed by Atmospheric Instrumentation Research before installation of either barometer.
2. Enter the nominal slope (5200 Pa/V) and the nominal offset (74000 Pa) in the appropriate columns of *calconst.xls*.

Electronic path calibration - (E1)

1. Modify *vbl.lst* so that the barometer channel is listed at the top of the file. Set NV (number of variables) in the first line to the number of channels to be calibrated, and ensure that the correct PCM stream is specified in *gencal.cap* (all meteorological channels were on stream 3).
2. Connect the precision voltage generator to the barometer output.
3. Run the *gc.bat* batch file which invokes both *gencal.exe* and *genfit.exe*. Collect samples for voltages ranging from 0 to 4.5 V in 0.5 V increments with two repetitions at each voltage level. The recorded input and output values are stored in the **.cao* input file. *Genfit.exe* computes slopes and offsets of the electronic path from the processor output to the computer in units of V/count and V, respectively. These values are stored in a temporary header file, **.hdr*. These slope and offset values are combined with the manufacturer-provided slope and offset stored in *calconst.xls* during the *buildhdr.bat* process to obtain units of engineering unit/count and counts, respectively.

Calibration frequency

The barometers were calibrated by the manufacturer prior to Phase V data collection. The electronic path calibration was performed prior to each series of data collection, which lasted less than 1 month.

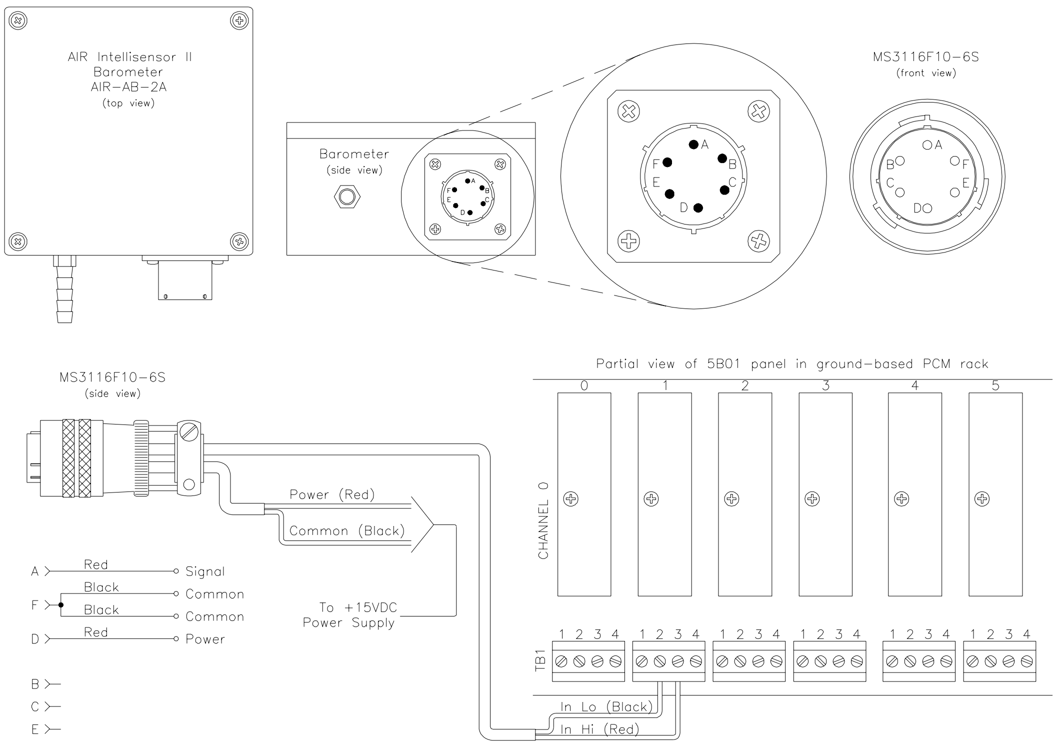
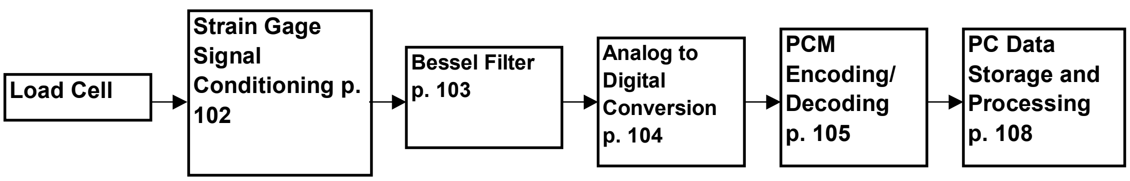


Figure 22. Barometer wiring diagram

Load Cell (Teeter Link)

Channel	ID Code	Description
223	TLINKF	Strain Teeter link force

Location	Teeter link, hub
Measurement type and units	Tensile and compressive load, N
Excitation	10 Vdc
Range	±10,000 lbs
Resolution	32 N/bit
Calibration method	Application of known loads (A3)
Sensor description	Hermetically sealed, universal tension and compression force sensor Transducer Techniques Model: HSW-10K



Note: The sign convention is such that positive teeter link force coincides with positive flap bending moment. Thus, compressive forces are positive.

Calibration Procedure

Application of known loads - (A3)

A custom jig was built in order to align two load cells in series and apply a load mechanically. One of the load cells (Transducer Techniques Model SW-10K) was connected to a digital meter, and the other load cell (Transducer Techinques HSW-10K) was placed in the data acquisition system in order to get a full-path calibration. Only the length of cable between the sensor and the data acquisition system differed from that used to collect data in the field.

1. Using the digital meter, loads were applied from –10,000 pounds to 10,000 pounds in 2500-lb increments and the count values noted. A linear regression analysis provided the slope and offset coefficients, which were entered manually in the master.hdr file.

Calibration frequency

This channel was calibrated prior to Phase V (spring 1998), and the same calibration coefficients were used for Phase V (fall 1998).

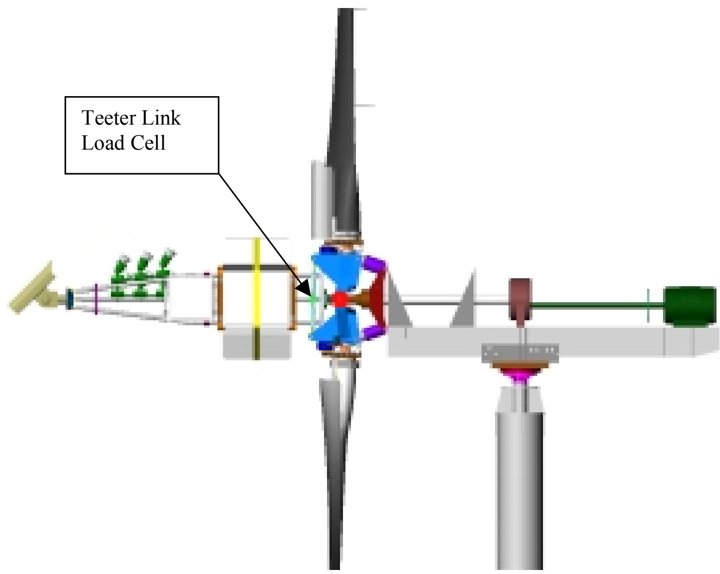


Figure 23. Teeter link load cell location

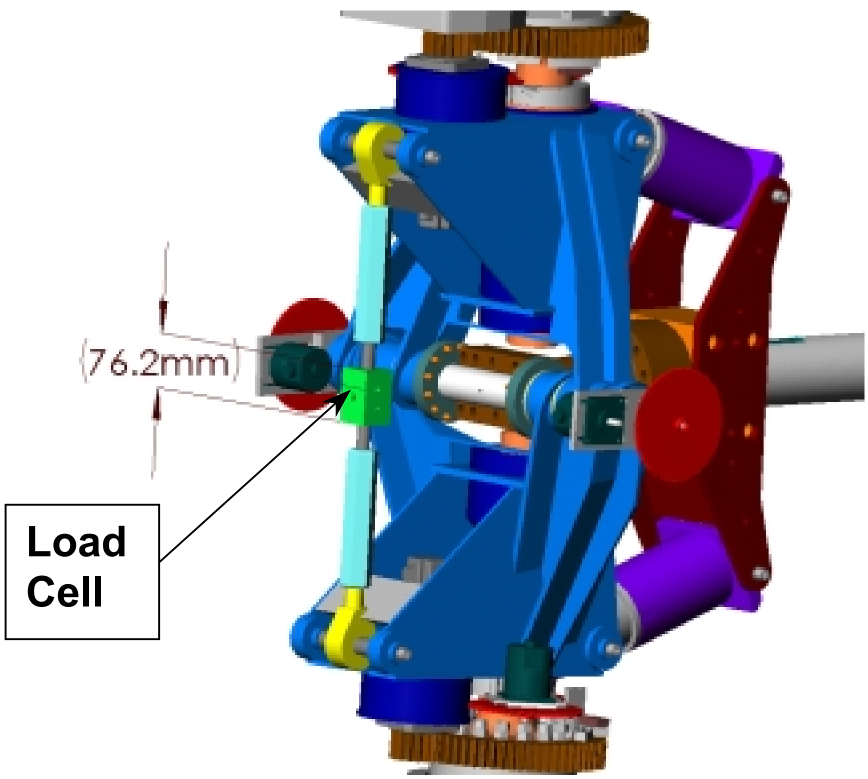
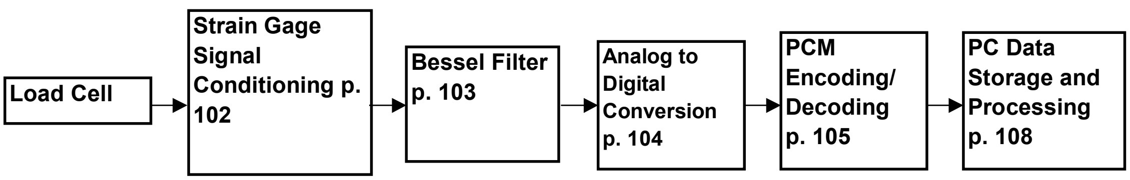


Figure 24. Teeter link load cell

Load Cell (Button Sensor)

Channel	ID Code	Description
229	B1TDF	Strain Blade 1 Teeter damper force
231	B3TDF	Strain Blade 3 Teeter damper force

Location	Teeter damper, one for each blade
Measurement type and units	Compressive load, N
Excitation	10 Vdc
Range	10,000 lbs
Resolution	30 N/bit
Calibration method	Application of known loads (A4); single point offset (S5)
Sensor description	Button force sensor Sensotec Model: 53/0239-08



Calibration Procedure

Application of known loads - (A4)

1. A custom jig was built in order to align both of the button sensors with the calibration load cell in series. A mechanical load was then applied. The calibration load cell (Transducer Techniques Model SW-10K) was connected to a digital meter, and the button load cells were placed in the data acquisition system in order to get a full-path calibration. This calibration was performed when the rotor was assembled on the ground. Only the length of cable between the sensor and the data acquisition system differed from that used to collect data in the field.
2. Using the digital meter, loads were applied from 0 lbs to 8,000 lbs in increments of 2000 lbs, and the count values noted. A linear regression analysis provided the slope and offset coefficients which were entered manually in the master.hdr file.

Single Point Offset - (S5)

1. During Phase V (fall 1998), the offset was determined by placing the rotor at 0° teeter angle which corresponds to zero load on the teeter dampers. The count values were noted and manually entered in the master.hdr file.

Calibration frequency

The slope and offset were calibrated prior to Phase V (spring 1998), and the same slope coefficient was used for Phase V (fall 1998). The zero offset was calibrated using the single-point offset method for Phase V (fall 1998).

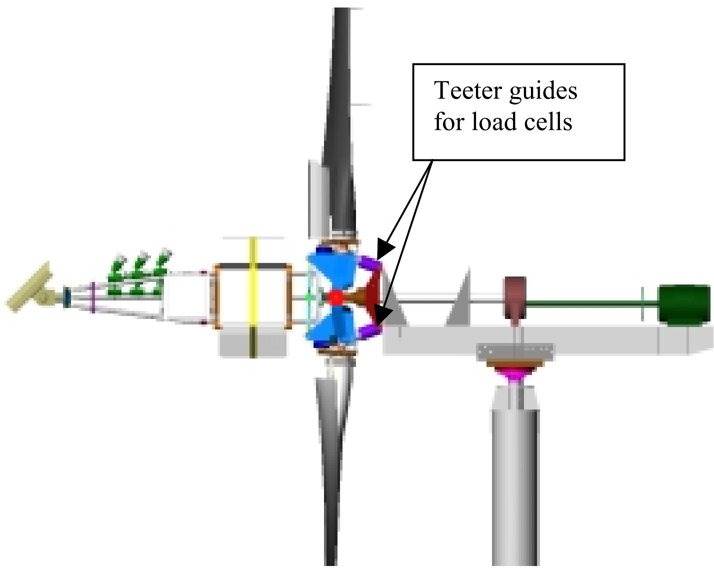


Figure 25. Teeter damper load cell locations

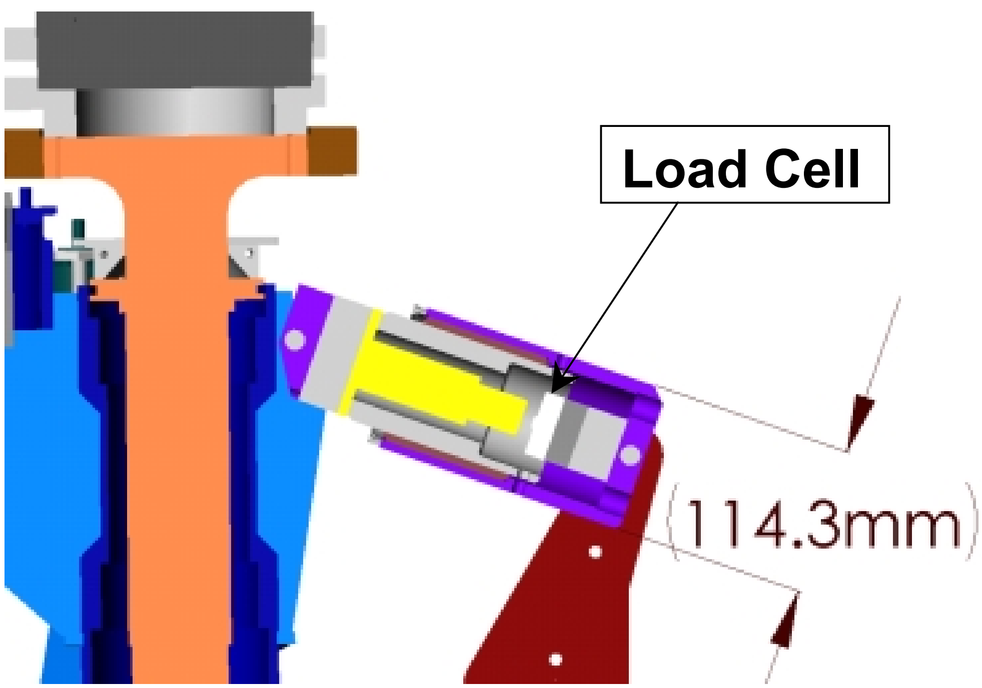
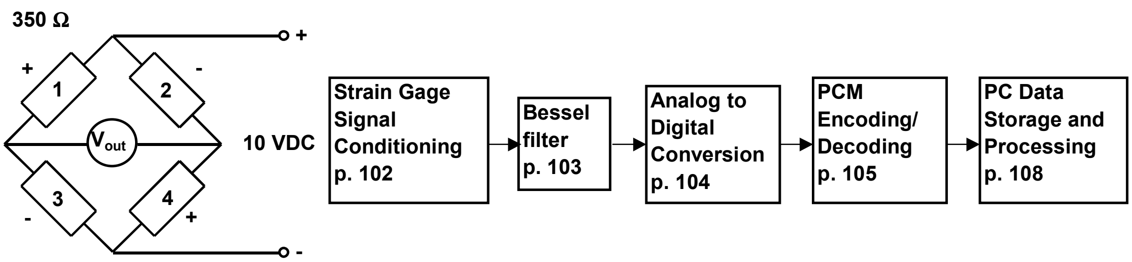


Figure 26. Teeter damper load cell cross-sectional view

Channel	ID Code	Description
215	HSXXB	Hub shaft X-X bending moment
217	HSYYB	Hub shaft Y-Y bending moment
219	HSTQ1	Hub shaft torque 1
221	HSTQ2	Hub shaft torque 2

Location	Hub shaft
Measurement type and units	Bending moment, Nm; torque, Nm
Excitation	10 Vdc
Range	± 50,000 με
Resolution	10,000 με / V
Calibration method	Application of known loads (A1)
Sensor description	Resistance = 350.0 ± 0.4% Ω Measurements Group, Inc. Model: LWK-06-W250B-350 (Bending) LWK-06-250D-350 (Torque)



Note: The hub shaft XX bending gauge has a positive peak when blade 3 is at 0° azimuth and a negative peak when blade 3 is at 180° azimuth. The hub shaft YY bending gauge has a positive peak when blade 3 is at 90° azimuth and a negative peak when blade 3 is at 270° azimuth. The hub shaft torque measurements are positive in the direction of rotation.

Calibration Procedures

Application of known loads (A1)

A custom jig was used for strain gauge calibrations in order to isolate load conditions to one direction only (flap or edge). The jig mounts on the blade slightly inboard of the attachment of the tip block. A cord is attached to the jig, and run over a pulley to the ground where weights are applied. One person in the man-lift mounts the jig on the blade and positions the man-lift so that the pulley is level and square with the cord attachment to the jig. Another person applies the weights in 20-lb increments from 0 to 100 lb. A third person operates the computer to collect samples at each load condition. The hub shaft bending gauges were calibrated by hanging weights from the boom in a similar manner. These procedures produce new slope values for the strain gauge measurements. Because the low-speed shaft bending gauges were oriented 120° out of phase of the hub shaft bending gauges, the slope values used for previous phases of data collection were used again for Phase V. The LSSYYB gauges were inoperable during the spring session of data collection, and they were replaced prior to the fall session. During the fall session, the low-speed shaft bending gauge slope values were calibrated by suspending weights from the boom.

Determination of the offset values was performed as in previous phases of the experiment. Essentially, the root flap and edge offsets were determined by placing each blade in a position where the respective load is zero. The offset for the low-speed shaft and hub shaft gauges was determined by recording cyclic bending moments and torque. The average over one complete rotation was equivalent to the offset under zero load.

The slope and offset values were inserted in a temporary header file called *strains.hdr*. This file is read during the *buildhdr* process, and the values are placed in the *master.hdr* file.

Slope coefficient calibration:

1. The man-lift person notifies ground people as to which blade and which direction (flap or edge) will be calibrated first. The computer person selects the appropriate channel(s) in *vbl.lst* to place at the top of the file. The number of channels to be collected is specified in the first line with NV, and the PCM stream on which the channels are contained is selected in *gencal.cap*. All of the strain gauges are on PCM stream 2 except the yaw moment strain gauges (NAYM), which are on PCM stream 3. The yaw moment channel (NAYM) is calibrated separately because it is on a different PCM stream than the other strain gauges. The low-speed shaft torque and both hub shaft torque channels (LSSTQ, HSTQ1, HSTQ2) are included with each of the edge-bending channels (B1REB, B3REB). The flap-bending gauges (B1RFB, B3RFB) are each calibrated alone. The hub shaft and low-speed shaft bending gauges are calibrated separately (HSXXB, HSYYB, LSSXXB, LSSYYB) by suspending weights from immediately downwind of the boom stiffener at rotor positions corresponding to pure bending for each gauge.
2. The *gencal* program is run while the weights are applied from 0 to 100 lb in 20-lb increments with three repetitions at each level. *Gencal* is run again while the weights are removed. The recorded weight and count values are stored in the **.cao* input files. A few seconds between application of the weight and collection of data allows any vibrations of the turbine to damp. This is done for both flap and edge directions for each of the blades to calibrate flap bending, edge bending, hub shaft torque, low-speed shaft torque, and yaw moment strain gauges. The weights are applied again in each of the above configurations to load the blades in both positive and negative directions. The weights are applied to the boom at rotor positions of 0°, 60°, 90°, 150°, 180° 240°, 270°, and 340° to load the hub-shaft and low-speed shaft bending gauges in both positive and negative directions.
3. Compute moments in Nm using the following formula:

$$M = \left(\frac{w * \left(R * 39.37 \frac{in}{m} - r \right)}{12 \frac{in}{ft}} \right) 1.35582 \frac{Nm}{ft \cdot lb}$$ where M= Bending moment (Nm),

   w = weight applied (0 to 100 lb), R = blade radius (5 m), and r = radial distance to strain gauge (17 in. from low-speed shaft to blade root gauges). The moment arm from the hub-shaft gauges to the point on the boom at which the load was applied is 91.5 in. This replaces the term in parentheses in the numerator of the above equation. Plot each curve in Excel, and perform a linear curve fit to determine the slope for both the positive and negative bending conditions for each strain gauge. Enter the average of the magnitude of the two slope values in the temporary header file, strains.hdr.

Offset coefficient calibration

1. All of the strain gauges except yaw moment were listed in two *vbl.lst* files for input to *gencal* (*gencal* is limited to input of 8 channels). A batch file was developed to run *gencal* with each of the two *vbl.lst* files to require only one rotation of the rotor. The instrumented blade was positioned at 30° increments over one complete rotational cycle. Three samples were obtained at each position. The blade flap angles were positioned to be equal corresponding to zero teeter angle.
2. The offset for flap-bending channels was determined by averaging the count value of each blade at 90° and at 270° where the flap load is 0 Nm. This number may be compared with the value obtained by averaging the loads at 0° and at 180° where the average load should be 0 Nm.
3. A similar procedure provided the offset values of the edge-bending channels. The average load at 0° and at 180° provided the zero offset while a comparison of the average load at 90° and 270° indicated if the procedure worked properly.
4. The low-speed shaft bending for both X-X and Y-Y axes, the hub-shaft bending for both X-X and Y-Y axes, both hub-shaft torque measurements, and the low-speed shaft torque average to zero over the complete rotational cycle. This average count value was used to determine the offset.
5. The yaw moment offset was determined by recording the count value when the yaw brake was released in zero wind conditions.
6. The count values obtained under zero-load conditions for each channel were multiplied by the corresponding slope value and entered in *strains.hdr*.

Note: The calibration pins must be removed during the blade edge pulls so that the hub shaft torque is not transferred through the pins. The pins must be installed during the blade flap pulls to maintain a 0° flap angle. During the spring calibrations of the hub-shaft torque slope coefficients, it was determined that the dampers were transferring some of the load to the low-speed shaft. A calibration performed without the dampers attached was repeatable once the damper attachment holes were reamed. However, during the fall calibrations, the slope values were not repeatable, and it was determined that the dampers were once again transferring the load to the low-speed shaft. Thus, the previously used slope values were inserted in *strains.hdr*, but new zero values were obtained for the fall campaigns.

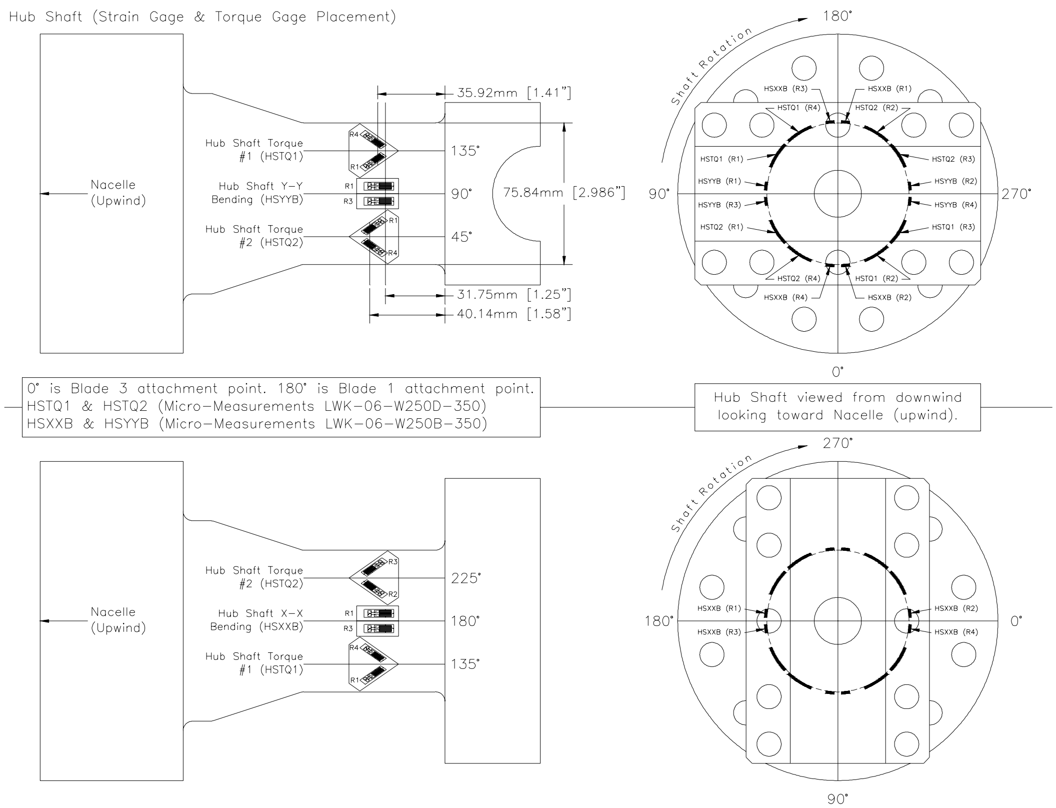


Figure 27. Hub-shaft strain gauge orientation

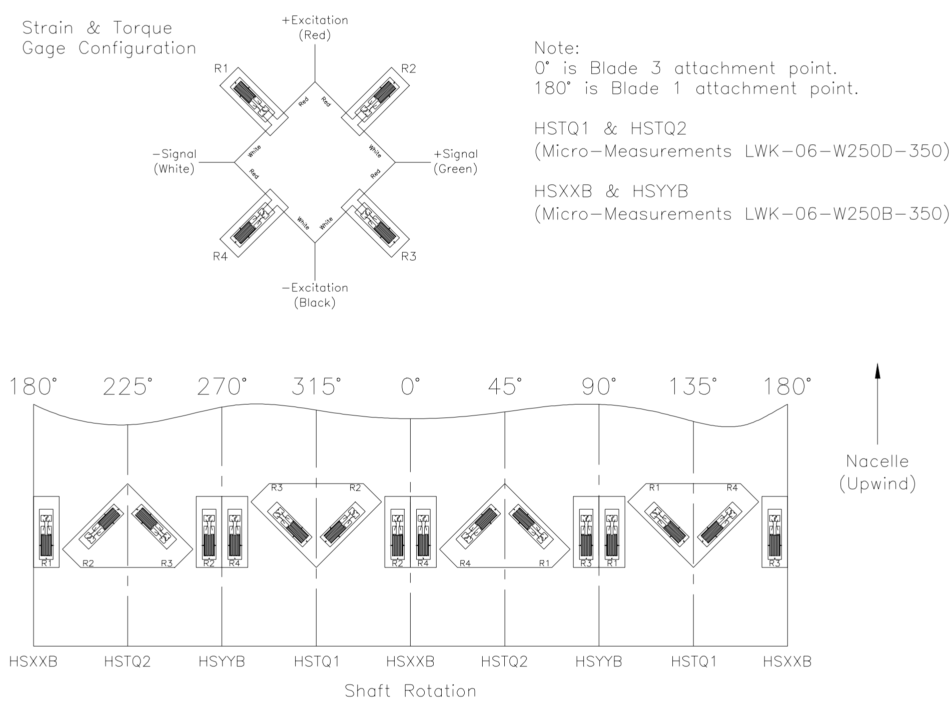
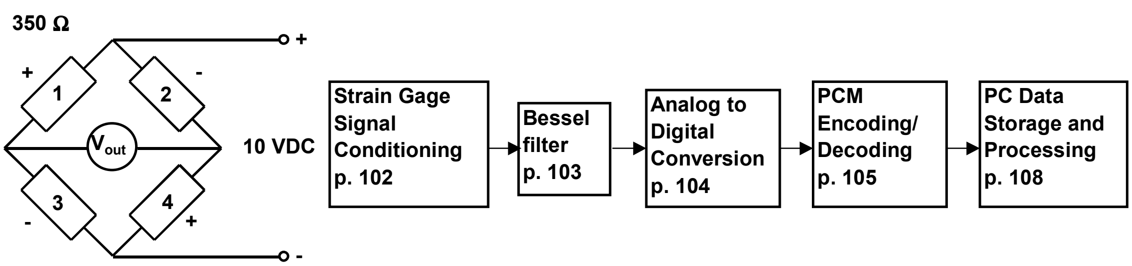


Figure 28. Plan view of hub shaft strain gauges

Channel	ID Code	Description
225	B1RFB	Blade 1 root flap-bending moment
227	B1REB	Blade 1 root edge-bending moment
233	B3RFB	Blade 3 root flap-bending moment
235	B3REB	Blade 3 root edge-bending moment

Location	Pitch shaft (8.6% span), 8360 Steel
Measurement type and units	Bending moment, Nm
Excitation	5Vdc
Range	± 5000 $\mu\varepsilon$
Resolution	2000 $\mu\varepsilon$ / V
Calibration method	Application of known loads (A1)
Sensor description	Resistance = 350.0 ± 0.4% Ω Measurements Group, Inc. Model: LWK-09-W250B-350



Note: Flap-bending moment is positive when a force acts in the downwind direction; the flap moment vector is parallel to the tip chord. Edge-bending moment is positive when a force acts in the direction of rotation; the edge moment vector is perpendicular to the tip chord.

Calibration Procedures (see p. 67)

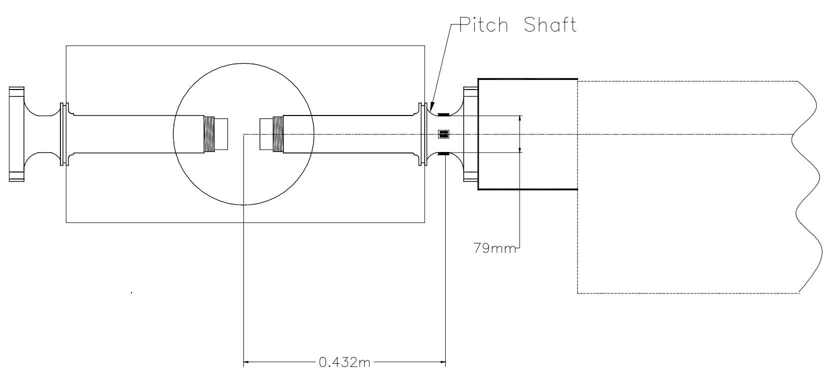


Figure 29. Root-bending gauges, side view

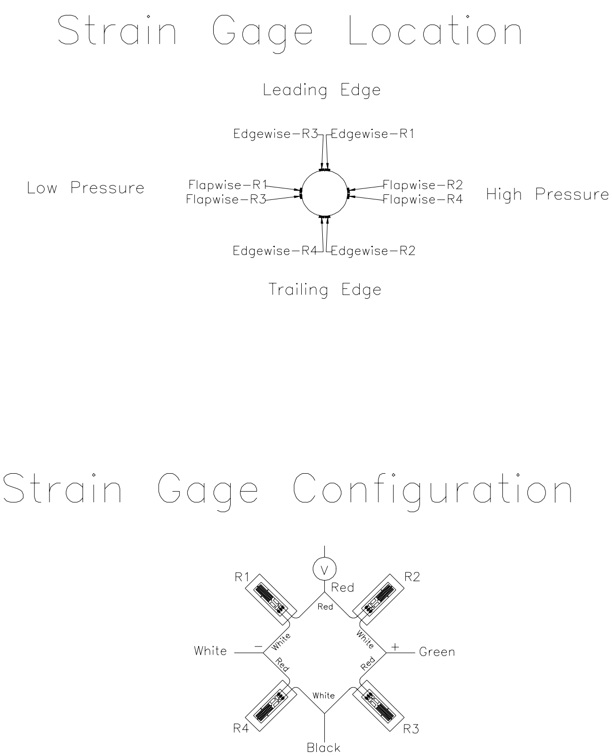
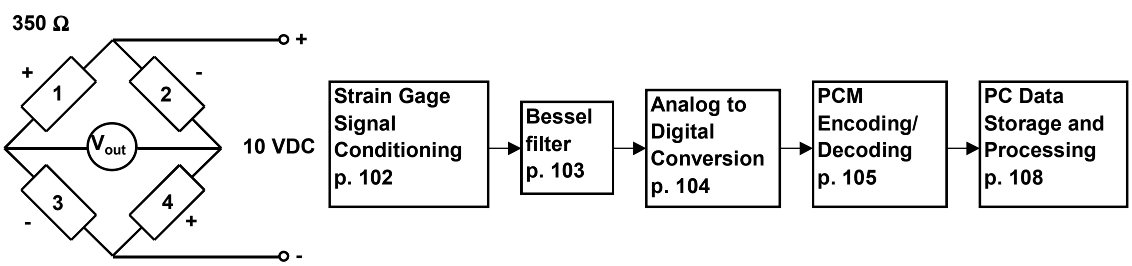


Figure 30. Root-bending strain gauge configuration

Strain Gauges (Low-speed shaft)

Channel	ID Code	Description
237	LSSXXB	X-X low-speed shaft bending moment
239	LSSYYB	Y-Y low-speed shaft bending moment
241	LSSTQ	Low-speed shaft torque

Location	Low-speed shaft
Measurement type and units	Bending moment, Nm; torque, Nm
Excitation	10 Vdc
Range	± 50,000 με
Resolution	10,000 με / V
Calibration method	Application of known loads (A1)
Sensor description	Resistance = 350.0 ± 0.4% Ω Measurements Group, Inc. Model: CEA-06-250UW-350 (LSS Bending) CEA-06-250US-350 (LSS Torque)



Note: The low-speed shaft XX bending gauge has a positive peak when blade 3 is at 240° azimuth and a negative peak when blade 3 is at 60° azimuth. The low-speed shaft YY bending gauge has a positive peak when blade 3 is at 150° azimuth and a negative peak when blade 3 is at 330° azimuth. The low-speed shaft torque measurement is positive in the direction of rotation.

Calibration Procedures (see p. 67)

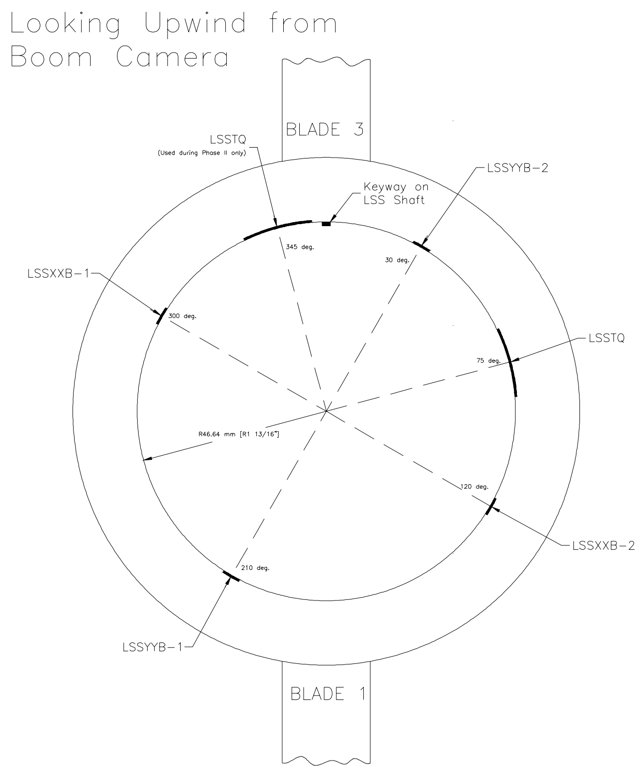


Figure 31. Low-speed shaft strain gauge positions

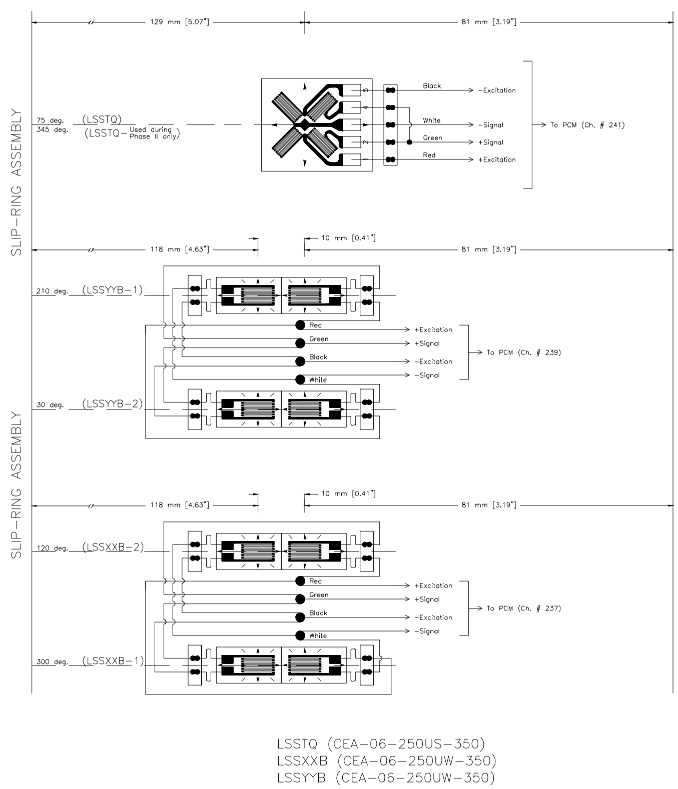


Figure 32. Low-speed shaft strain gauge configuration

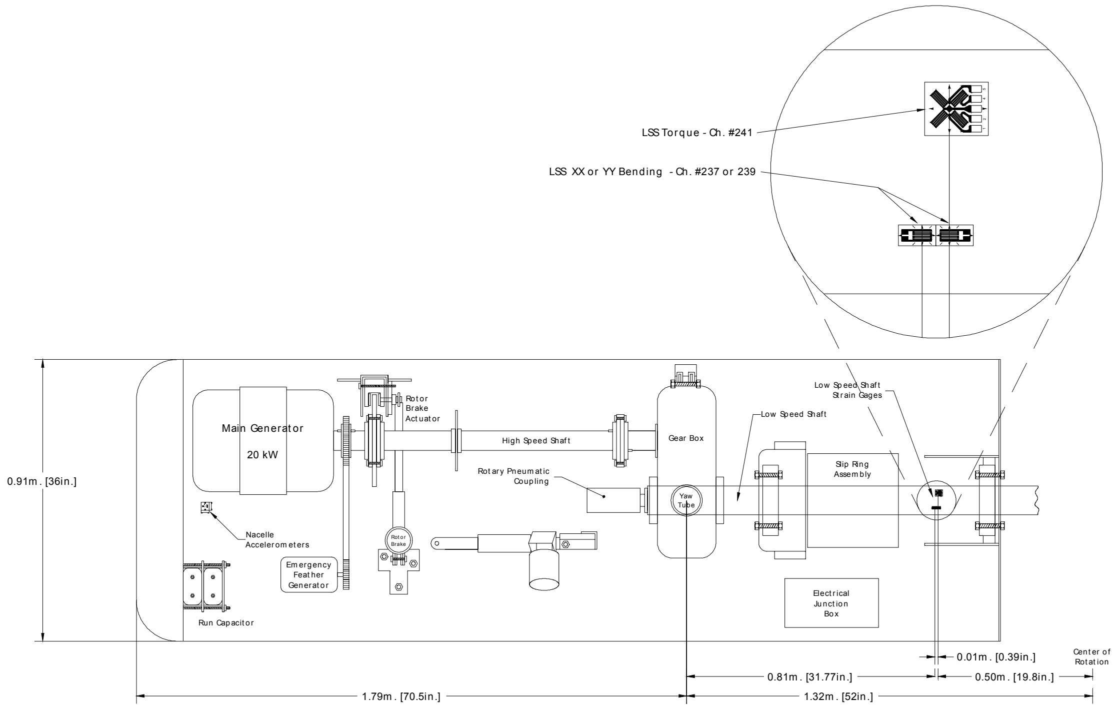
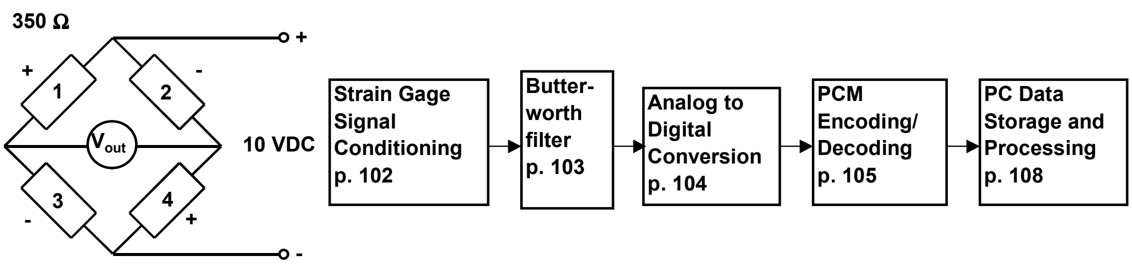


Figure 33. Low-speed shaft strain gauge location within nacelle

Strain Gauges (Yaw Moment)

Channel	ID Code	Description
342	NAYM	Nacelle yaw moment

Location	Arms of yaw brake mechanism
Measurement type and units	Bending moment, Nm
Excitation	10 Vdc
Range	
Resolution	
Calibration method	Application of known loads (A1)
Sensor description	Resistance = 350.0 ± 0.4% Ω
	Measurements Group, Inc.
	Model:



Note: yaw moment is positive due to positive yaw error.

Calibration Procedures (see p. 67)

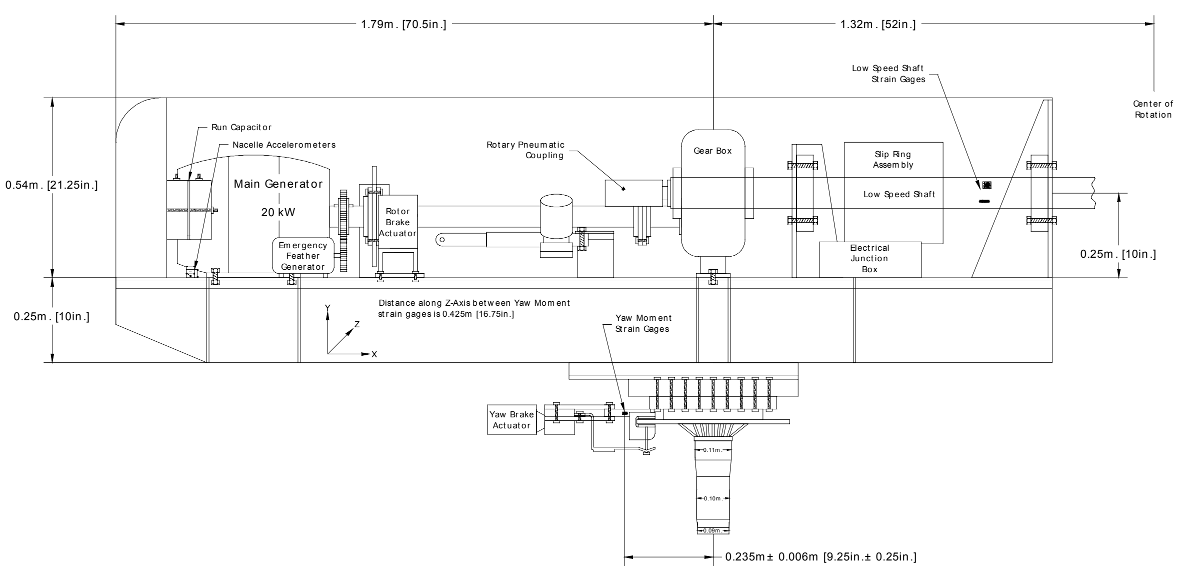
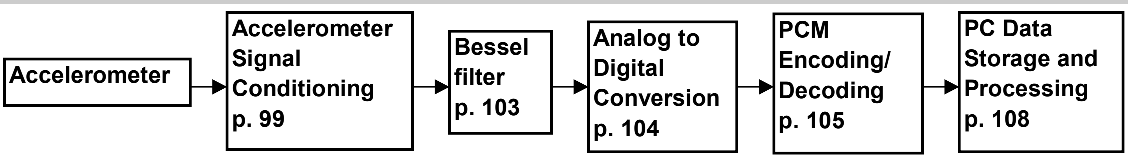


Figure 34. Yaw moment strain gauge configuration

Channel	ID Code	Description
201	B1ACFL	Blade 1 tip accelerometer – flap
203	B1ACED	Blade 1 tip accelerometer – edge
209	B3ACFL	Blade 3 tip accelerometer – flap
211	B3ACED	Blade 3 tip accelerometer – edge
336	NAACYW	Nacelle accelerometer – yaw
338	NAACFA	Nacelle accelerometer - fore-aft sway
340	NAACPI	Nacelle accelerometer – pitch

Location	Blade tip, inside tip block; nacelle bedplate near generator
Measurement type and units	linear acceleration, g's
Excitation	15 Vdc
Range	±2 V = ±10 g
Sensitivity	200 mV / g
Calibration method	Manufacturer specifications (M8) and electronic path calibration (E1)
Sensor description	Variable capacitance accelerometer Endevco Corporation Model: 7290A-10



Calibration Procedure

Manufacturer specifications - (M8)

1. A calibration was performed by Endevco Corporation before installation of the accelerometers.
2. Enter the sensitivity as recorded by Endevco and the offset (0 g) in the appropriate columns of *calconst.xls*.

Electronic path calibration (E1)

1. Modify *vbl.lst* so that the accelerometer channels are listed at the top of the file. Set NV in the first line to the number of channels to be calibrated, and ensure that the correct PCM stream is specified in *gencal.cap* (PCM stream 2 for blade accelerometers and PCM stream 3 for nacelle accelerometers). Because the nacelle accelerometers and the blade tip accelerometers are on different PCM streams, they must be separated into two **.cao* files.
2. Connect the precision voltage generator to the accelerometer output prior to the signal conditioners.

3. Run the *gc* batch file which invokes both *gencal* and *genfit*. Collect samples for voltages ranging from –0.9 to 0.9 V in 0.2 V increments for nacelle accelerometers (-0.8 to 0.8 in 0.2 V increments for blade accelerometers) with two repetitions at each voltage level. The recorded input and output values are stored in the **.cao* input file. *Genfit* computes slopes and offsets of the electronic path from the processor output to the computer in units of volts / count and volts, respectively. These values are stored in a temporary header file, **.hdr*. These slope and offset values are combined with the manufacturer-provided slope and offset during the *buildhdr* process to obtain units of engineering unit/count and counts, respectively.

Calibration frequency

The accelerometers were calibrated prior to installation. An electronic path calibration was performed prior to each series of data collection, which lasted less than 1 month.

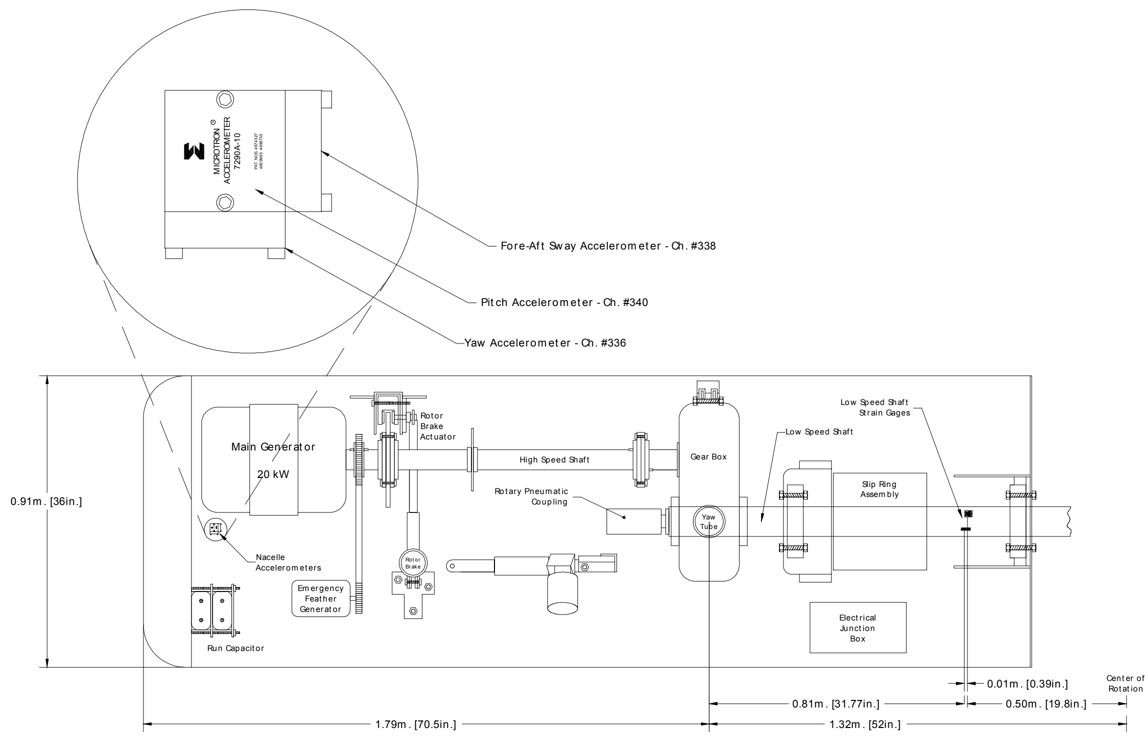


Figure 35. Nacelle accelerometer configuration

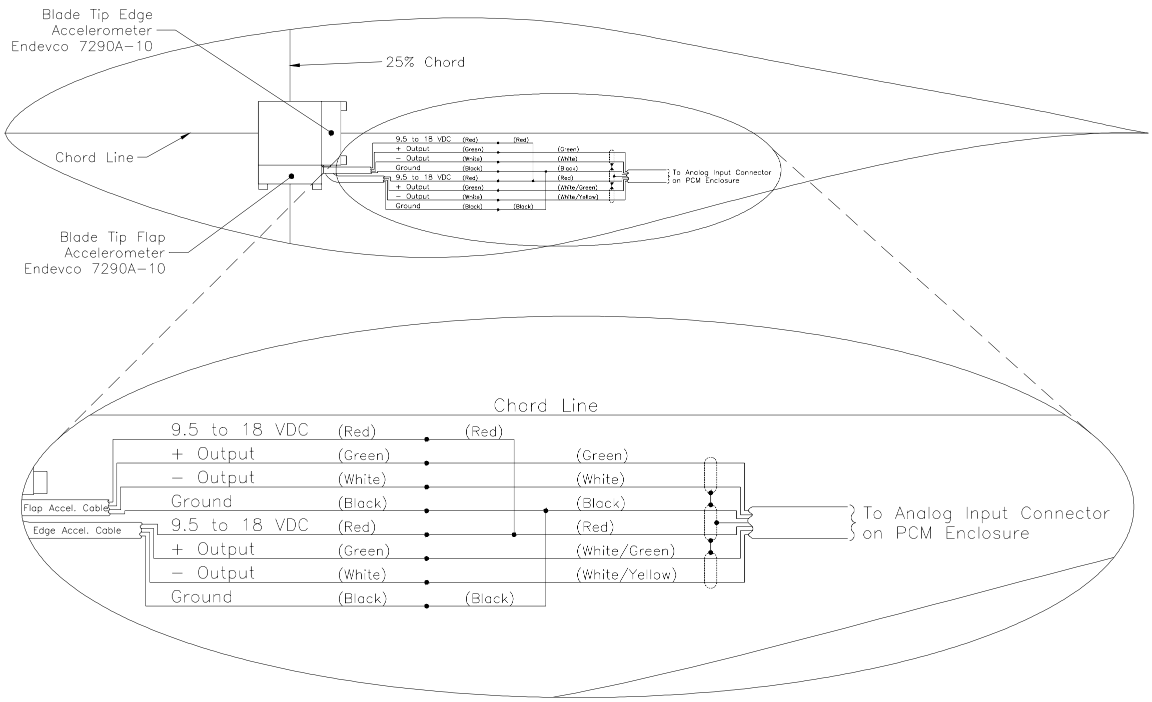
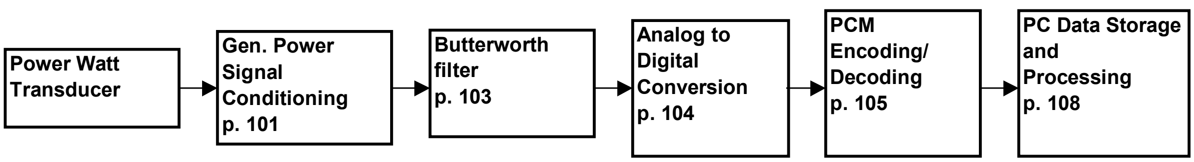


Figure 36. Blade tip accelerometer configuration

Power

Channel	ID Code	Description
332	GENPOW	Generator power

Location	Power handling cabinet inside data shed
Measurement type and units	Electrical power, kW
Range	-40 kW to 40 kW = -5 V to 5 V
Resolution	8 kW/V
Calibration method	Manufacturer specifications (M7) and electronic path calibration (E1)
Sensor description	AC Watt Transducer 3-phase, 3-wire 50/60-Hz Ohio Semitronics, Inc. Model: PC5-63C (DOE#: 00502C)



Calibration Procedure

Manufacturer specifications - (M7)

1. A calibration was performed by NREL Calibration Laboratory before installation of the power watt transducer.
2. Enter the slope (8 kW/V) and the offset (0 kW) in the appropriate columns of *calconst.xls*.

Electronic path calibration - (E1)

1. Modify *vbl.lst* so that the power channel is listed at the top of the file. Set NV (number of variables) in the first line to the number of channels to be calibrated, and ensure that the correct PCM stream is specified in *gencal.cap* (PCM stream 3).
2. Connect the precision voltage generator to the power transducer output.
3. Run the *gc.bat* batch file which invokes both *gencal.exe* and *genfit.exe*. Collect samples for voltages ranging from –4.5 to 4.5 V in 1 V increments with two repetitions at each voltage level. The recorded input and output values are stored in the **.cao* input file. *Genfit.exe* computes slopes and offsets of the electronic path from the processor output to the computer in units of V/count and V, respectively. These values are stored in a temporary header file, **.hdr*. These slope and offset values are combined with the manufacturer-provided slope and offset during the *buildhdr.bat* process to obtain units of engineering unit/count and counts, respectively.

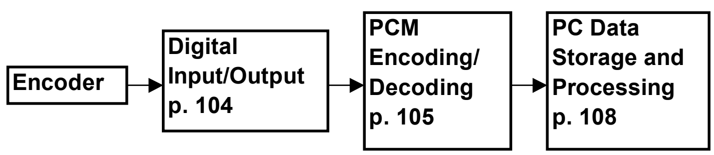
Calibration frequency

The transducer was calibrated in the laboratory prior to installation. The electronic path calibration was performed prior to each series of data collection, which lasted less than 1 month.

Digital Position Encoders (Rotor)

Channel	ID Code	Description
253	B1PITCH	Blade 1 pitch angle
257	B3PITCH	Blade 3 pitch angle
349	B3AZI	Blade 3 azimuth angle
351	YAW	Turbine yaw angle

Location	Root attachment of each blade; low-speed shaft in nacelle; yaw axis.
Measurement type and units	angular position, degrees
Power requirement	15 Vdc
Range	360° = 4096 counts
Resolution	0.08789 °/count
Calibration method	Manufacturer specifications (M9) and single-point offset determination (S3)
Sensor description	Digital, gray code resolver Accuracy: ±1/2 Count (LSB), worst case BEI Motion Systems Company Model: R25-4096-24



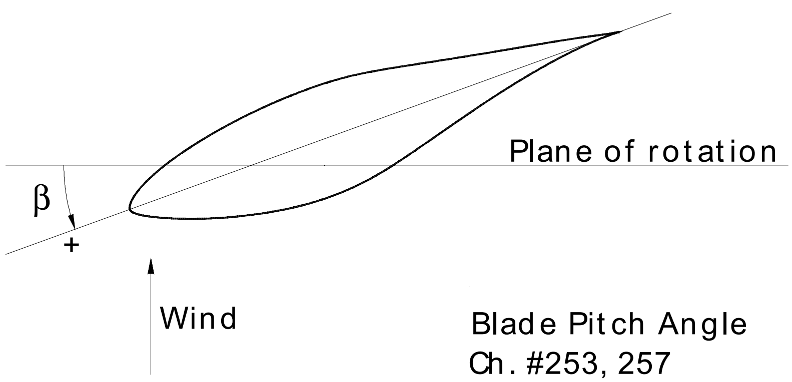


Figure 37. Blade pitch angle orientation

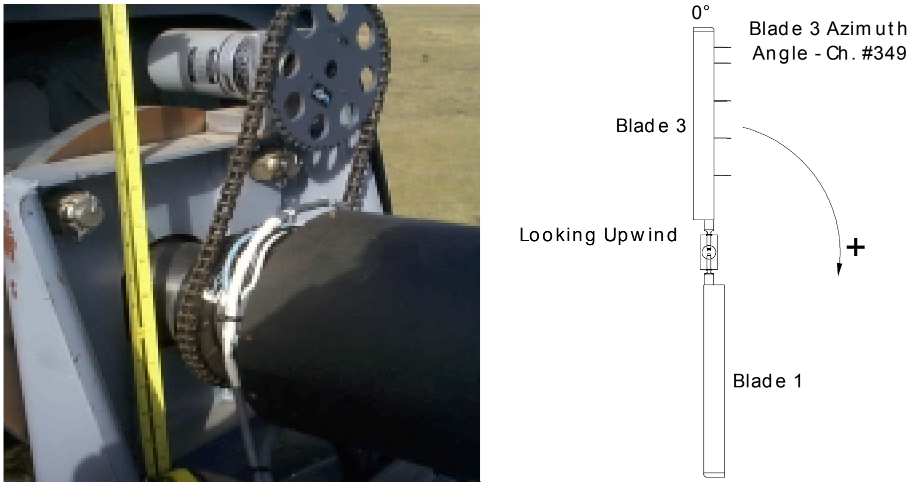


Figure 38. Azimuth angle encoder photograph and orientation

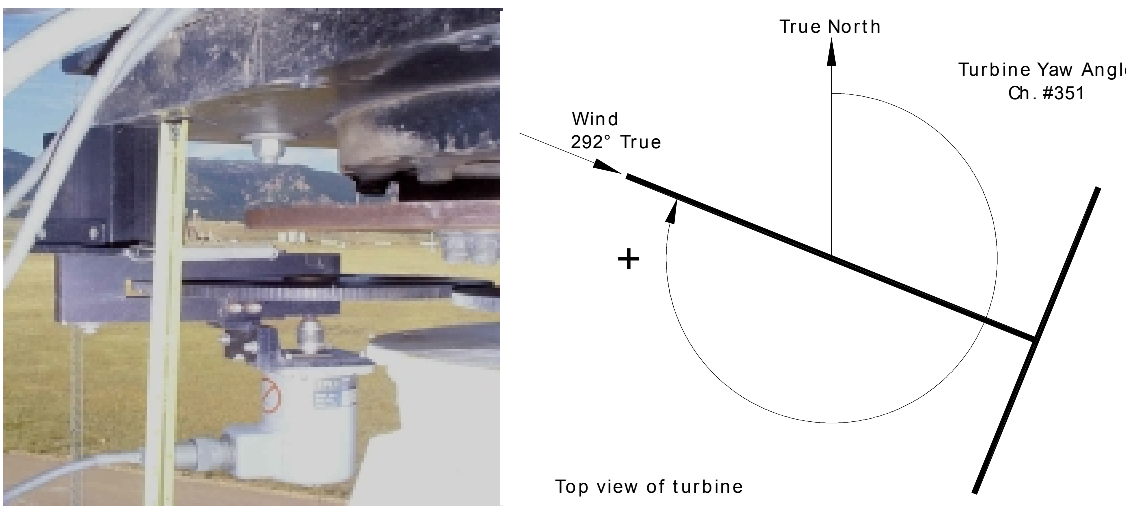


Figure 39. Yaw angle encoder photograph and orientation

Calibration Procedure

Manufacturer specifications - (M9)

1. A calibration was performed by BEI Motion Systems before installation of all digital position encoders.
2. Enter the slope (0.08789°/count) in the appropriate columns of *calconst.xls*.

Single-point offset determination - (S3) - (This is a two-person operation requiring one person in the man-lift to position the blades or turbine and one person on the ground to operate the computer.)

1. The man-lift person notifies ground person which encoder is to be calibrated. A reference point is used to determine the offset for each encoder as follows:
   a. Each blade is individually pitched to 0°, and an Angle-star is used to measure the exact pitch angle.

b. The nacelle is aligned by eye with the north met tower (292° from true north) to determine the yaw angle offset.
c. The instrumented blade is aligned by eye with the tower (180°) to determine the azimuth angle offset.

2. The difference between the data acquisition system angle and the known angle is determined in counts. This value is added to the current count value listed in *calconst.xls*. A new *master.hdr* file is created using the macros *Write ang.hdr* and *Write convert.v2u* along with the program *vupdate.exe*. The angle is then repositioned and the difference obtained. If the difference is greater than 2-3 counts, the process is repeated.

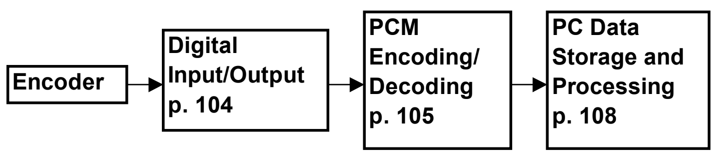
Calibration frequency

The blade pitch, yaw angle, and azimuth angle offsets were determined prior to each series of data collection.

Digital Position Encoders (Hub)

Channel	ID Code	Description
251	B1FLAP	Blade 1 flap angle
255	B3FLAP	Blade 3 flap angle

Location	Mounted on hub outboard of teeter bearing
Measurement type and units	angular position, degrees
Power requirement	15 Vdc
Range	45° (restricted by damper)
Resolution	0.0110°/count
Calibration method	Manufacturer specifications (M13) and single-point offset determination (S6)
Sensor description	Digital, gray-code resolver Accuracy: ±1/2 Count (LSB), worst case BEI Motion Systems Company Model: RAS-25



Calibration Procedure

Manufacturer specifications - (M13)

1. A calibration was performed by BEI Motion Systems before installation of all digital position encoders.
2. Enter the slope (360 °/(4096 counts*(8 gear-ratio))) in the appropriate columns of *calconst.xls*.

Single-point offset determination - (S6) - (This is a two-person operation requiring one person in the man-lift to insert the calibration pins and one person on the ground to operate the computer.)

1. Man-lift person notifies ground person which encoder is to be calibrated. A reference point is used to determine the offset for each encoder as follows:
2. The difference between the data acquisition system angle and the known angle is determined in counts. This value is added to the current count value listed in *calconst.xls*. A new *master.hdr* file is created using the macros *Write ang.hdr* and *Write convert.v2u* along with the program *vupdate*. The angle is then repositioned and the difference obtained. If the difference is greater than 2-3 counts, the process is repeated.

Calibration frequency

All encoders were calibrated by the manufacturer prior to Phase V data collection. The single-point offset determination was done prior to each series of data collection.

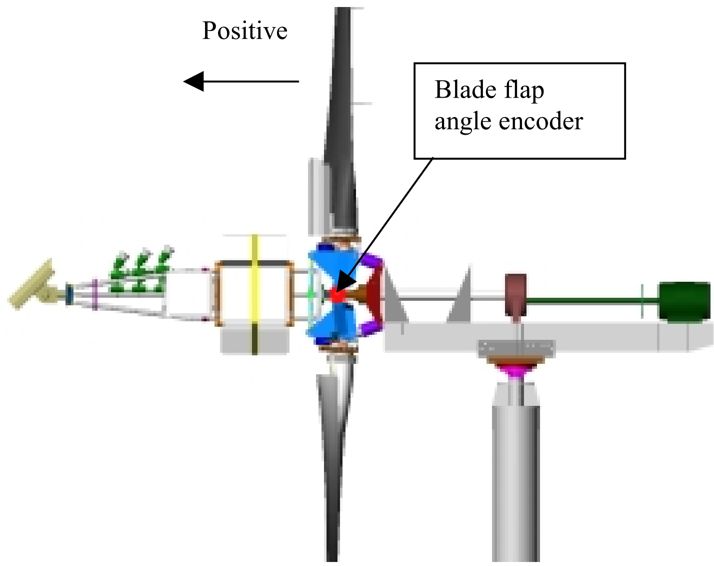


Figure 40. Blade flap angle encoder location

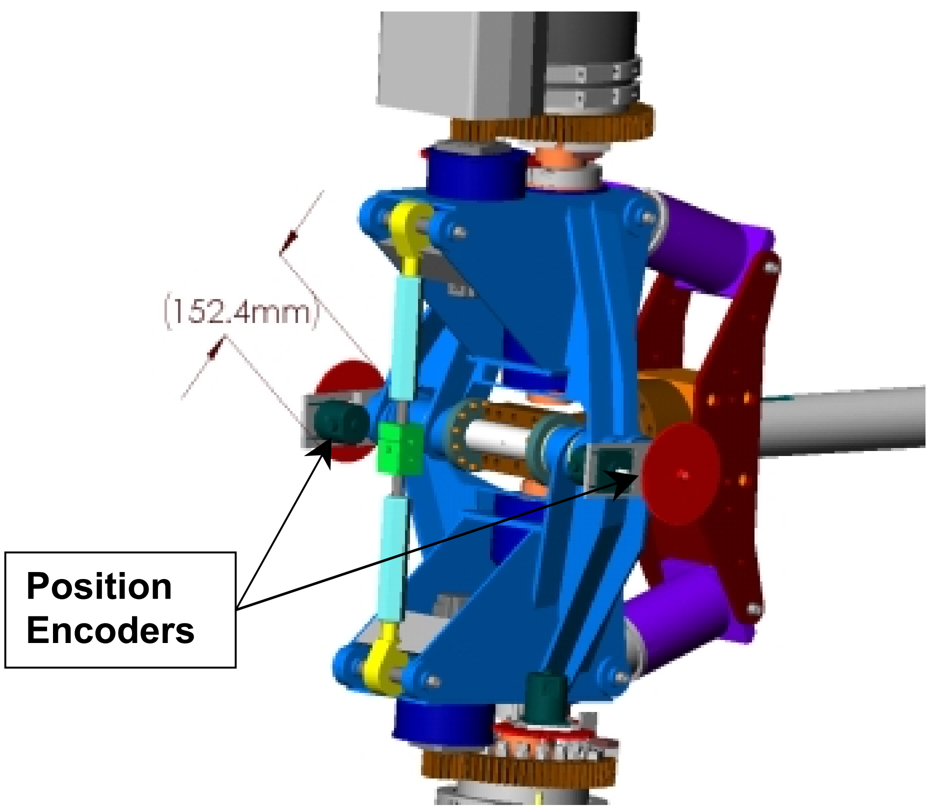


Figure 41. Blade flap angle close-up view

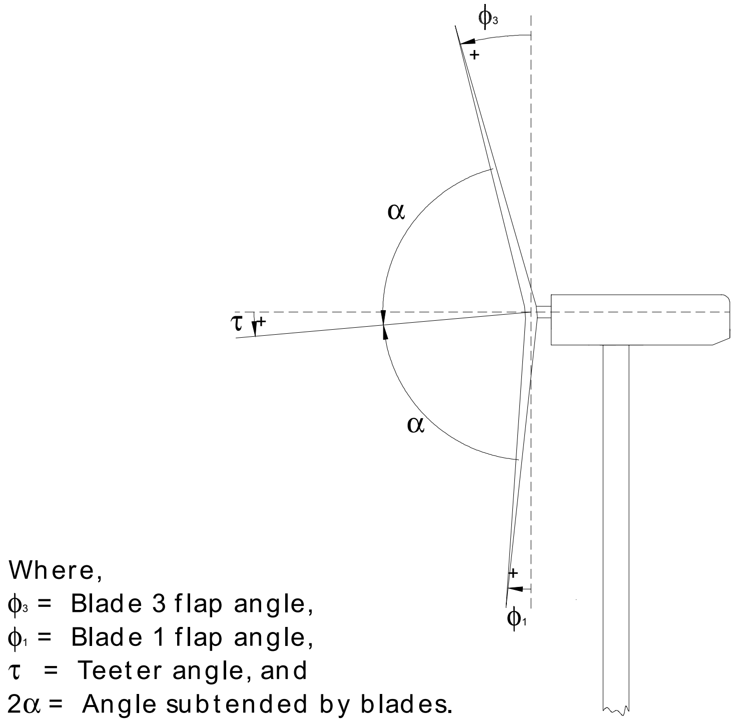
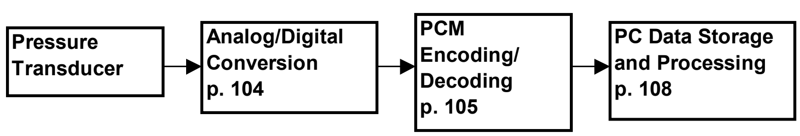


Figure 42. Blade flap angle convention

Pressure Transducers (30% and 47% span)

Channel	ID Code	Description
000-050	Ptt30ccc	Surface pressures at 30%, 36%, and 41% span
(even)	Ptt36ccc	tt = transducer tap number
	Ptt41ccc	ccc = % chord pressure tap location
001-051	Ptt47ccc	Surface pressures at 47%, 52%, and 58% span
(odd)	Ptt52ccc	tt = transducer tap number
	Ptt58ccc	ccc = % chord pressure tap location
052-060	5Hx34	5-hole probe at 34% span
(even)		x = designation of hole in 5-hole probe
053-061	5Hx51	5-hole probe at 51% span
(odd)		x = designation of hole in 5-hole probe

Location	Within blade 3 at approximately 30% span and 47% span
Measurement type and units	pressure difference between surface or probe and hub
Power requirement	5 Vdc, ±12 Vdc
Range	±2500 Pa (10" H_2O) = ±5 V
Resolution	500 Pa/V
Calibration method	Application of known pressures (A2)
Sensor description	32-channel electronic pressure scanner Scan rate: up to 20,000 readings/second Pressure Systems Model: ESP-32



Note:

1. Small pressure taps were installed in the surface of the blade skin during manufacturing. Each opening was mounted flush to the airfoil surface and was 0.6731 mm in diameter.
2. Stainless-steel tubes, 0.45 m in length, were installed inside the blade's skin during manufacturing to carry surface pressures to the pressure transducer. A short piece of plastic tubing joined the tubes to the transducers.
3. Gain amplifications and phase effects that occur as a function of tube frequency and tube length were measured. These effects were not significant up to a frequency of 50 Hz, and the measured pressure data showed no appreciable information above 50 Hz (Butterfield, Musial, and Simms 1992).

Calibration Procedures

Application of known pressures - (A2)

This calibration is designed to provide an accurate slope calibration of the complete pressure system. The pressure system controller is invoked to provide NIST-traceable reference pressures at all pressure ports. The pressures ramp up and down across the measurement range. Linear regression provides calibration coefficients that are automatically updated in *master.hdr* before data acquisition. This calibration is performed immediately before and after each 10-minute segment of data.

1. The batch file (*go.bat*) that initiates the process of collecting data begins a pressure calibration. After the turbine has been rotating for a few minutes, the temperature variations are minimized. The syringe in a hub-mounted instrumentation box applies a pressure to each transducer at once. Pressures were applied at -0.9, -0.7, -0.5, -0.3, -0.2, -0.1, 0.1, and 0.2 psi. The actual pressure applied to the transducers is measured with the Mensor digital differential pressure transducer. A linear regression analysis provides slope and offset values, which are incorporated in *master.hdr*. The calibration is also automatically performed once the 10-minute data segment has been collected. During consecutive runs, the post-calibration of one data segment may also serve as the pre-calibration for the next data segment.

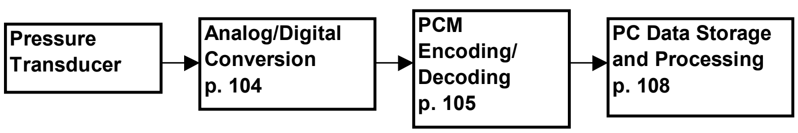
Table 22. Pressure Tap Chord Locations

Pressure Tap Number	% chord	Surface	tt	ccc
1	100%	Trailing edge	01	100
2	92%	Upper	02	92U
4	80%	Upper	04	80U
6	68%	Upper	06	68U
8	56%	Upper	08	56U
10	44%	Upper	10	44U
11	36%	Upper	11	36U
12	28%	Upper	12	28U
13	20%	Upper	13	20U
14	14%	Upper	14	14U
15	10%	Upper	15	10U
16	8%	Upper	16	08U
17	6%	Upper	17	06U
18	4%	Upper	18	04U
19	2%	Upper	19	02U
20	1%	Upper	20	01U
21	0.5%	Upper	21	.5U
22	0%	Leading edge	22	000
23	0.5%	Lower	23	.5L
24	1%	Lower	24	01L
25	2%	Lower	25	02L
26	4%	Lower	26	04L
27	6%	Lower	27	06L
28	8%	Lower	28	08L
30	14%	Lower	30	14L
31	20%	Lower	31	20L
32	28%	Lower	32	28L
34	44%	Lower	34	44L
36	68%	Lower	36	68L
38	92%	Lower	38	92L

Pressure Transducers (63% span)

Channel	ID Code	Description
100-150	Ptt63ccc	Surface pressures at 63%, 69%, and 74% span
(even)	Ptt69ccc	tt = transducer tap number
	Ptt74ccc	ccc = % chord pressure tap location
152-160	5Hx67	5-hole probe at 67% span
(even)		x = designation of hole in 5-hole probe

Location	Within blade 3 at approximately 63% span
Measurement type and units	pressure difference between surface or probe and hub
Power requirement	5 Vdc, ±12 Vdc
Range	±5000 Pa (20” H_2O) = ±5 V
Resolution	1000 Pa / V
Calibration method	Application of known pressures (A2)
Sensor description	32-channel electronic pressure scanner Scan rate: up to 20,000 readings/second Pressure Systems Model: ESP-32

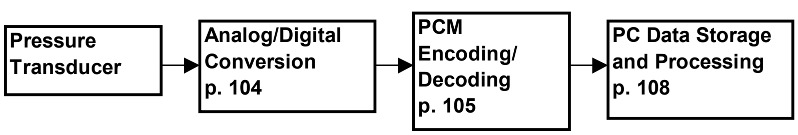


Calibration Procedure (see p. 88)

Pressure Transducers (80% and 95% span)

Channel	ID Code	Description
101-145	Ptt80ccc	Surface pressures at 80%, 85%, and 90% span
(odd)	Ptt85ccc	tt = transducer tap number
	Ptt90ccc	ccc = % chord pressure tap location
153-161	5Hx84	5-hole probe at 84% span
(odd)		x = designation of hole in 5-hole probe
200-250	Ptt95ccc	Surface pressures at 95%, 92%, and 98% span
(even)	Ptt92ccc	tt = transducer tap number
	Ptt98ccc	ccc = % chord pressure tap location
252-260	5Hx91	5-hole probe at 91% span
(even)		x = designation of hole in 5-hole probe

Location	Within blade 3 at approximately 80% span and 95% span
Measurement type and units	pressure difference between surface or probe and hub
Power requirement	5 Vdc, ±12 Vdc
Range	±10,342 Pa (1.5 psi) = ±5 V [±6894 Pa, (1.0 psi) = ±5 V at 80% span during fall 1998 series]
Resolution	2068 Pa / V (1379 Pa / V at 80% span during fall 1998 series)
Calibration method	Application of known pressures (A2)
Sensor description	32-channel electronic pressure scanner Scan rate: up to 20,000 readings/second Custom made for ±1.5 psi range Pressure Systems Model: ESP-32



Calibration Procedure (see p. 88)

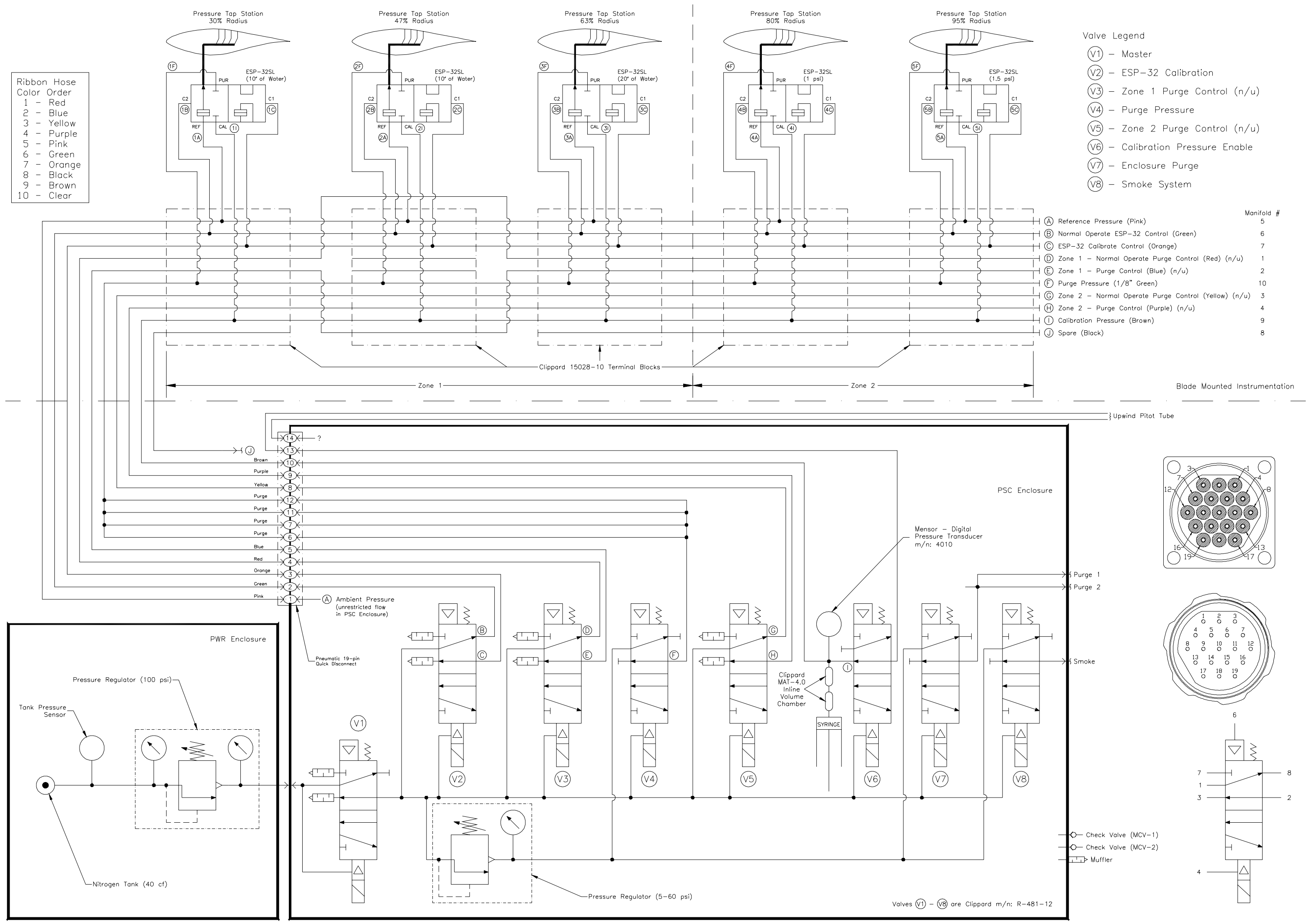


Figure 43. Pneumatic layout for fall 1998 data collection.

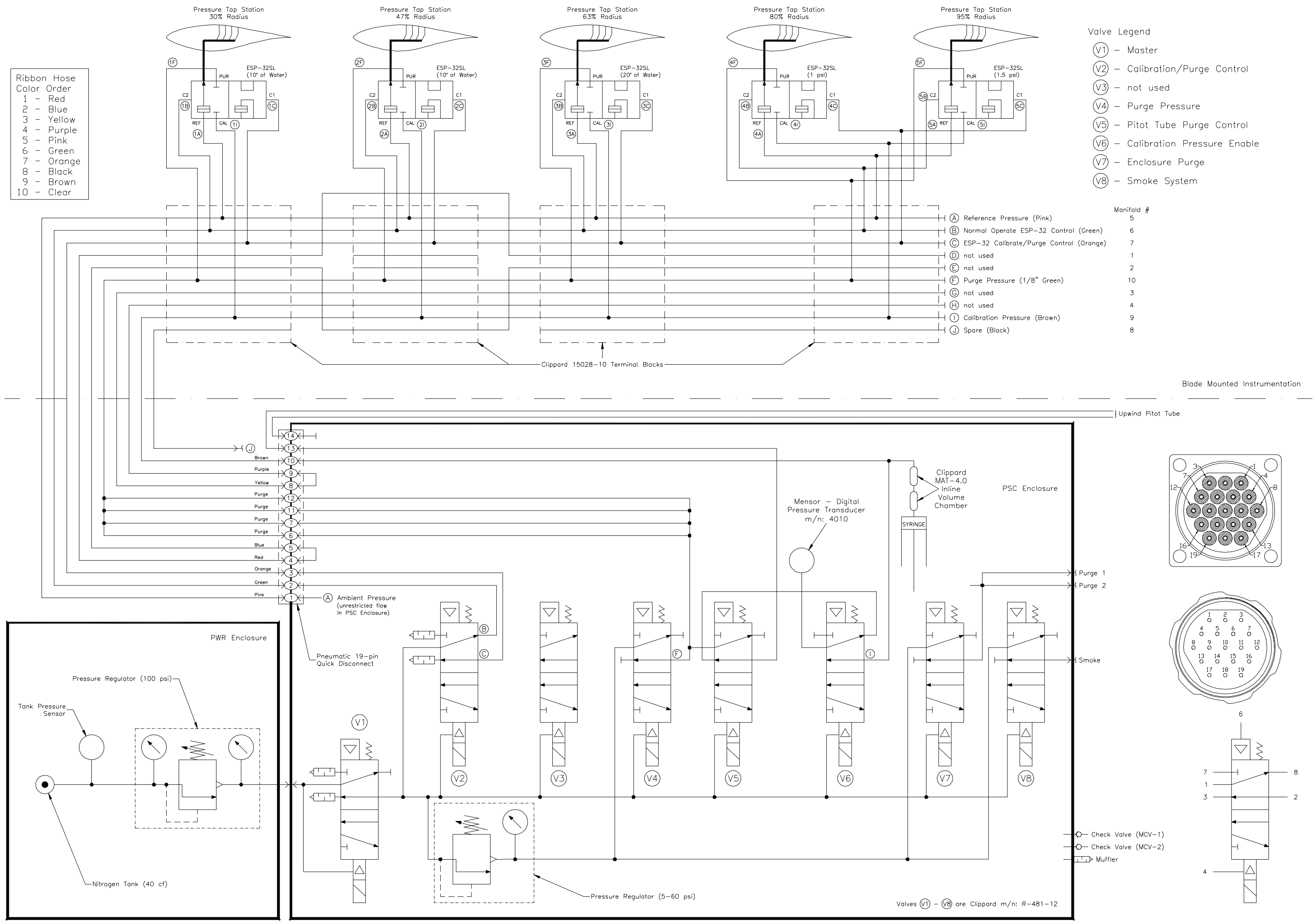
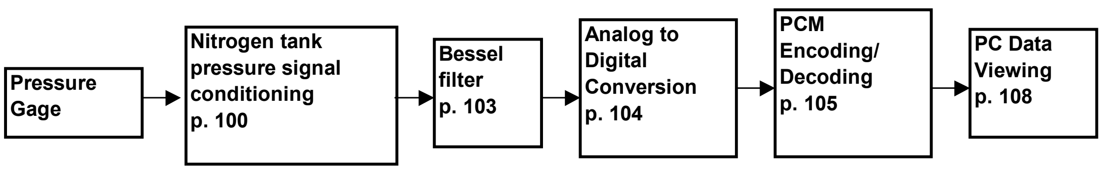


Figure 44. Pneumatic layout for spring 1998 data collection.

Channel	ID Code	Description
213	N/A	Analog nitrogen tank pressure

Location	Rotor package
Measurement type and units	pressure inside nitrogen tank, Pa
Power requirement	
Range	0 to 2000 psig
Resolution	
Calibration method	
Sensor description	



Calibration frequency

The pressure gauge was calibrated prior to Phase III. This channel is needed only to determine when the tank is nearly empty. The nitrogen is used to purge the pressure lines periodically. This channel is not recorded.

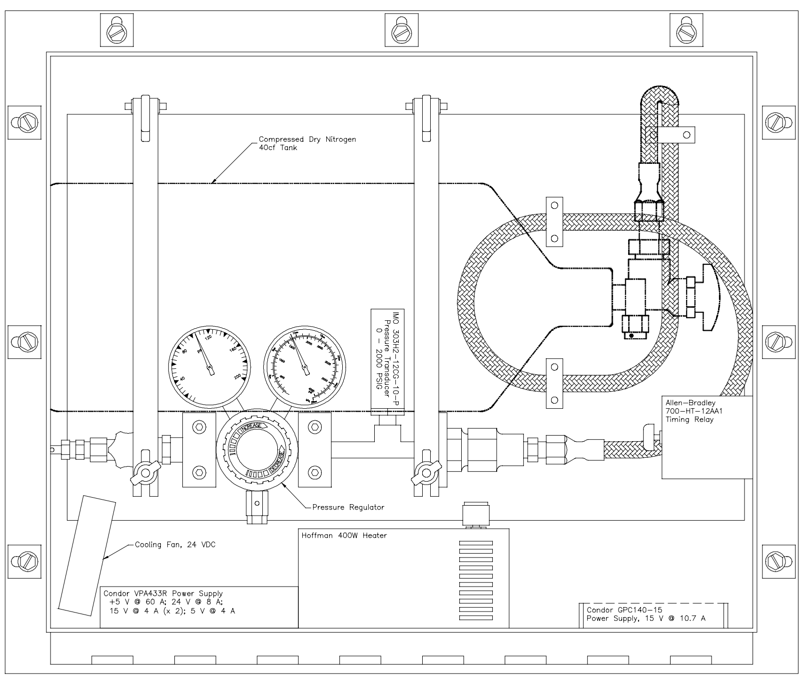
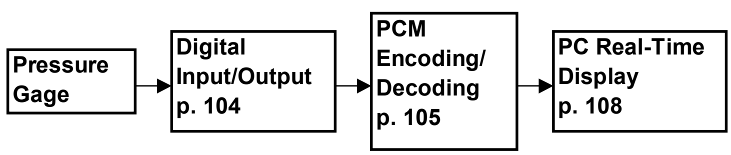


Figure 45. Nitrogen tank enclosure

Digital Differential Reference Pressure

Channel	ID Code	Description
259	VBL176	Digital first 12 bits from Δ pressure
261	VBL178	Digital last 12 bits from Δ pressure

Location	Rotor package
Measurement type and units	Calibration reference pressure and static differential pressure, Pa
Power requirement	12 Vdc
Range	±2 psig (±13,790 Pa)
Resolution	0.42 Pa/bit
Calibration method	Manufacturer (M11)
Sensor description	Digital pressure transducer 16 bit binary output Accuracy: 0.01% full scale Mensor Corporation Model: 4010



Calibration Procedure

Manufacturer specifications - (M11)

1. A calibration was performed by Mensor Corporation before installation of either digital pressure transducer.
2. The zero offset was determined by opening a valve, which provided the instrumentation box pressure to both sides of the Mensor. The tare value was adjusted to eliminate the difference.

Calibration frequency

The differential pressure transducers were calibrated prior to each series of data collection, which lasted less than 1 month. The zero offset was usually determined each day of data collection.

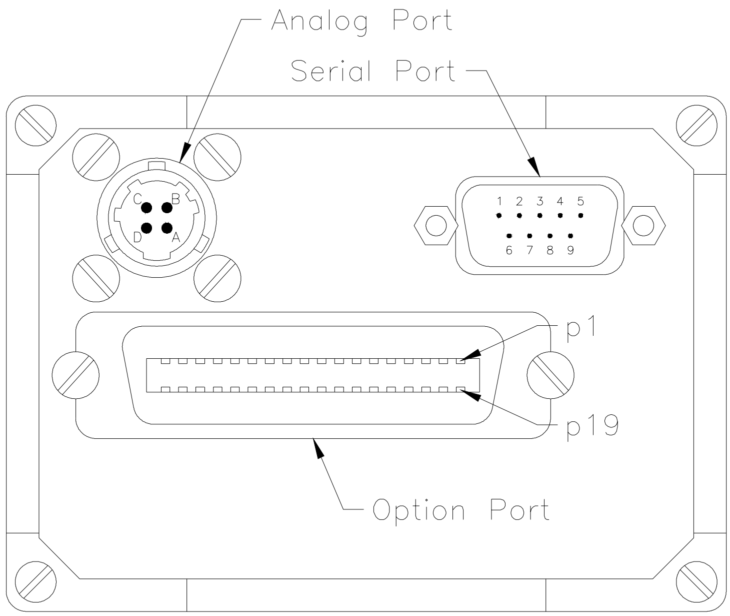


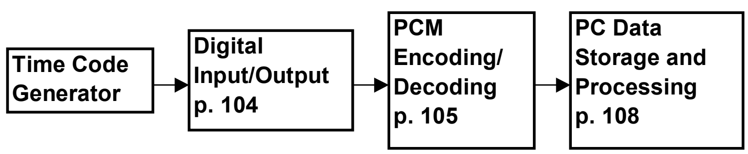
Figure 46. Mensor electrical ports

Figure 47. Upwind probe

Time Code Generator

Channel	ID Code	Description
353	DAY	Clock - day
355	HOUR	Clock - hour
357	MINUTE	Clock - minute
359	SECOND	Clock - second
361	MILLISEC	Clock - millisecond

Location	Met rack in data shed
Measurement type and units	Time, day, hour, minute, second, and millisecond
Power requirement	120 V AC
Calibration method	Manufacturer (M12)
Sensor description	Time code generator formats: IRIG-A, IRIG-B, IRIG-C, IRIG-E, IRIG-H frequency stability: ±5 ppm Model: 9310-804



Calibration Procedure

Manufacturer specifications - (M12)

1. A calibration was performed by the manufacturer before installation.

Calibration frequency

The time code generator was calibrated prior to Phase III data collection. However, prior to each series of data collection (or in the event of a power failure), the clock was set using atomic clock readings.

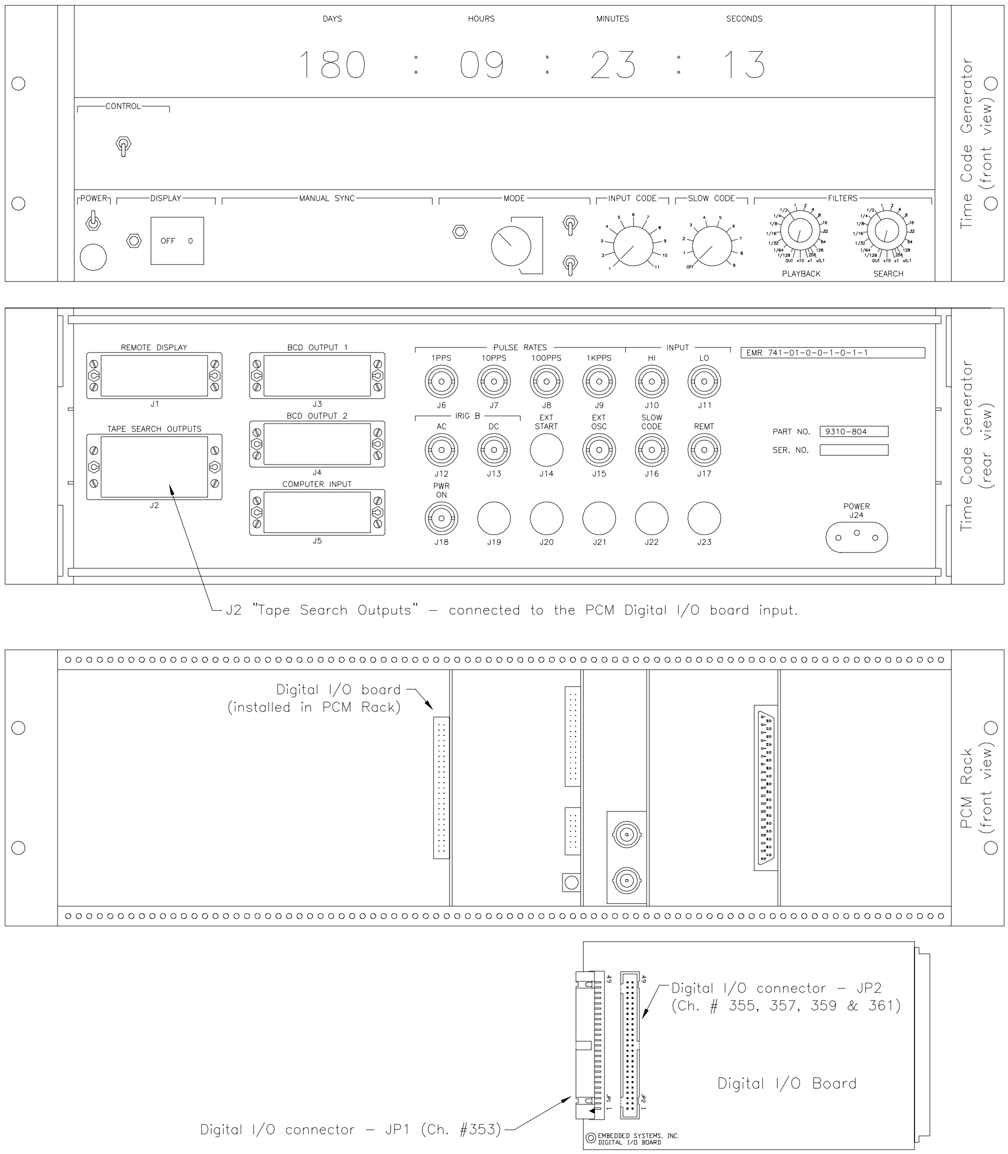


Figure 48. Time code generator

Accelerometer Signal Conditioning

Channel	Description
201, 203, 209, 211, 336-340 (even)	Accelerometers in blade tips and nacelle
Location	Rotor package for blade accelerometers; Met rack for nacelle accelerometers
Input level	± 1 Vdc
Output level	± 5 Vdc
Description	Isolated wide-band voltage input signal conditioning Analog Devices, Inc. Model: 5B01 (backplane), 5B41-01 (input module)

Nitrogen Tank Pressure Signal Conditioning

Channel	Description
213	Nitrogen tank pressure

Location	Rotor package
Input level	± 10 Vdc
Output level	± 5 Vdc
Description	Isolated wide-band voltage input signal conditioning Analog Devices, Inc. Model: 5B01 (backplane), 5B41-03 (input module)

Power Transducer and Barometric Pressure Signal Conditioning

Channel	Description
332	Generator power
334	Barometric pressure

Location	Met rack in data shed
Input level	± 5 Vdc
Output level	± 5 Vdc
Description	Isolated wide-band voltage input signal conditioning
	Analog Devices, Inc.
	Model: 5B01 (backplane), 5B41-02 (input module)

Strain Gauge Signal Conditioning

Channel	Description
215-241 (odd)	Blade root, yaw moment, hub shaft, and low-speed shaft strain gauges; teeter damper and teeter link load cells
Location	Rotor package
Input level	Isolated strain gauge input
Output level	± 5 Vdc
Description	
	Analog Devices, Inc. Model: 5B01 (backplate), 5B38-01 (input module)

Butterworth Filter

Channel	Description
300-334 (even), 342	Low-pass, 8th order, Butterworth 10-Hz filter
Location	Met rack in data shed
Description	Anti-alias filter ±15V power requirement Passband remains flat until 0.7 of Fc (-3 dB frequency), and then roll-off monotonically at a rate of 48 dB/oct AVENS Signal Equipment Corp. Model: AF-16 (container), AMLP8B10HZ

Bessel Filter

Channel	Description
336-340 (even), 344-350 (even)	Low-pass, 8th order, Bessel 100-Hz filter
Location	Met rack in data shed; rotating instrumentation package
Description	Anti-alias filter ±15V power requirement Passband remains flat until 0.1 Fc, and then roll-off monotonically to 20 dB at 2.5 Fc AVENS Signal Equipment Corp. Model: AF-16 (container), AMLP8L100HZ

Note: Yaw moment (342) is Butterworth, but all other strain gauges are Bessel.

Analog / Digital Conversion

Channel	Description
000-061, 100-161, 200-260 (even), 201-241 (odd), 300-342 (even)	All analog channels
Location	Met rack in data shed; rotating instrumentation package
Description	Instrumentation amplifier gain 0.9 Sample and hold capability 7 µs, 12-bit analog-to-digital conversion 4.250 V reference with 10-ppm accuracy that is adjusted within ±2 mV Custom built by Embedded Systems

Digital Input / Output

Channel	Description
251-261 (odd), 349-361 (odd)	Position encoders, time code generator
Location	Met rack in data shed; rotating instrumentation package
Description	Digital parallel Custom built by Embedded Systems

Channel	Description
All channels	Encode/decode digital data
Location	Met rack in data shed; rotating instrumentation package
Encode	CPU encoder board with 400 kbits/sec capability Encodes 24 bits at one time; no storage capacity Bi-Phase L Filtered at 400 kHz Signal level ±2.5 V Custom built by Embedded Systems
Decode	Phase lock loop Software set buffer size which uses direct memory access (DMA) to place data in computer memory when the buffer is full Number of buffers is also variable. Custom built by Apex Systems

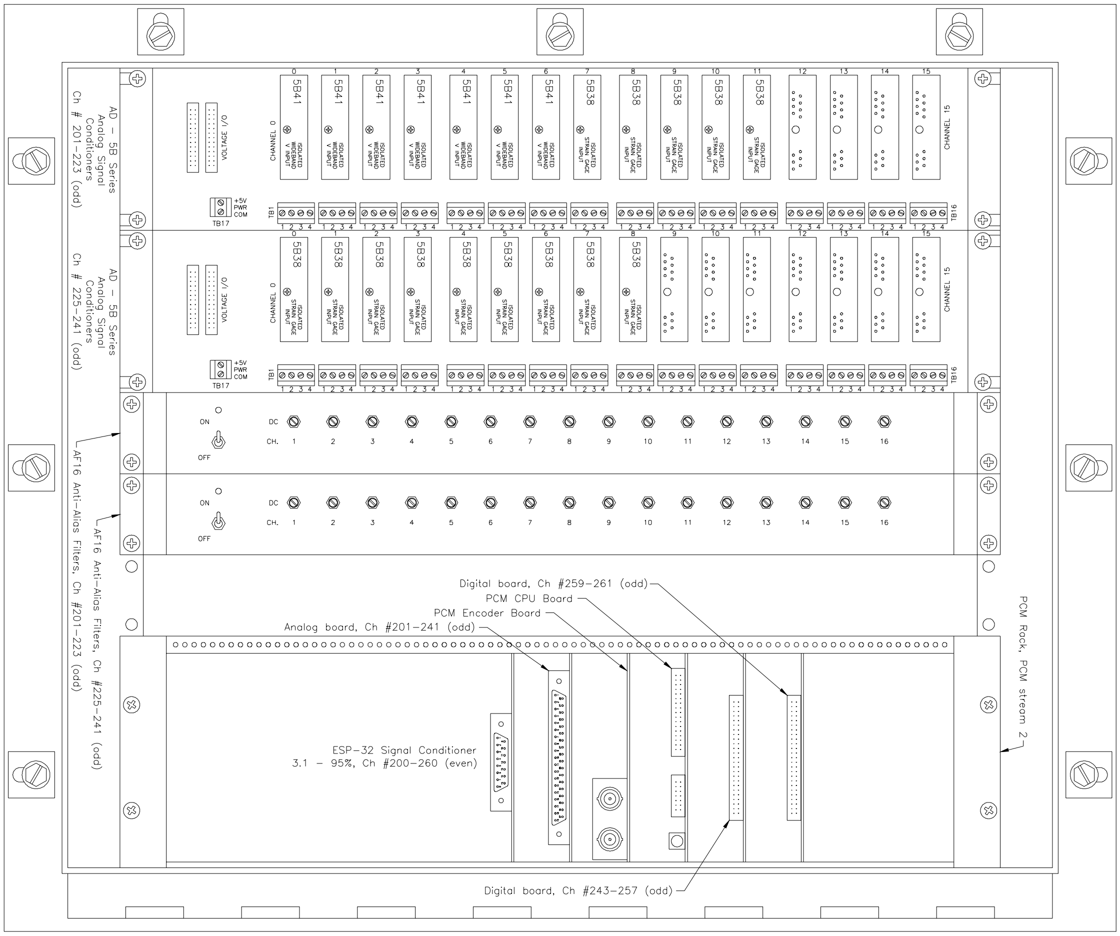


Figure 49. Rotor based PCM enclosure

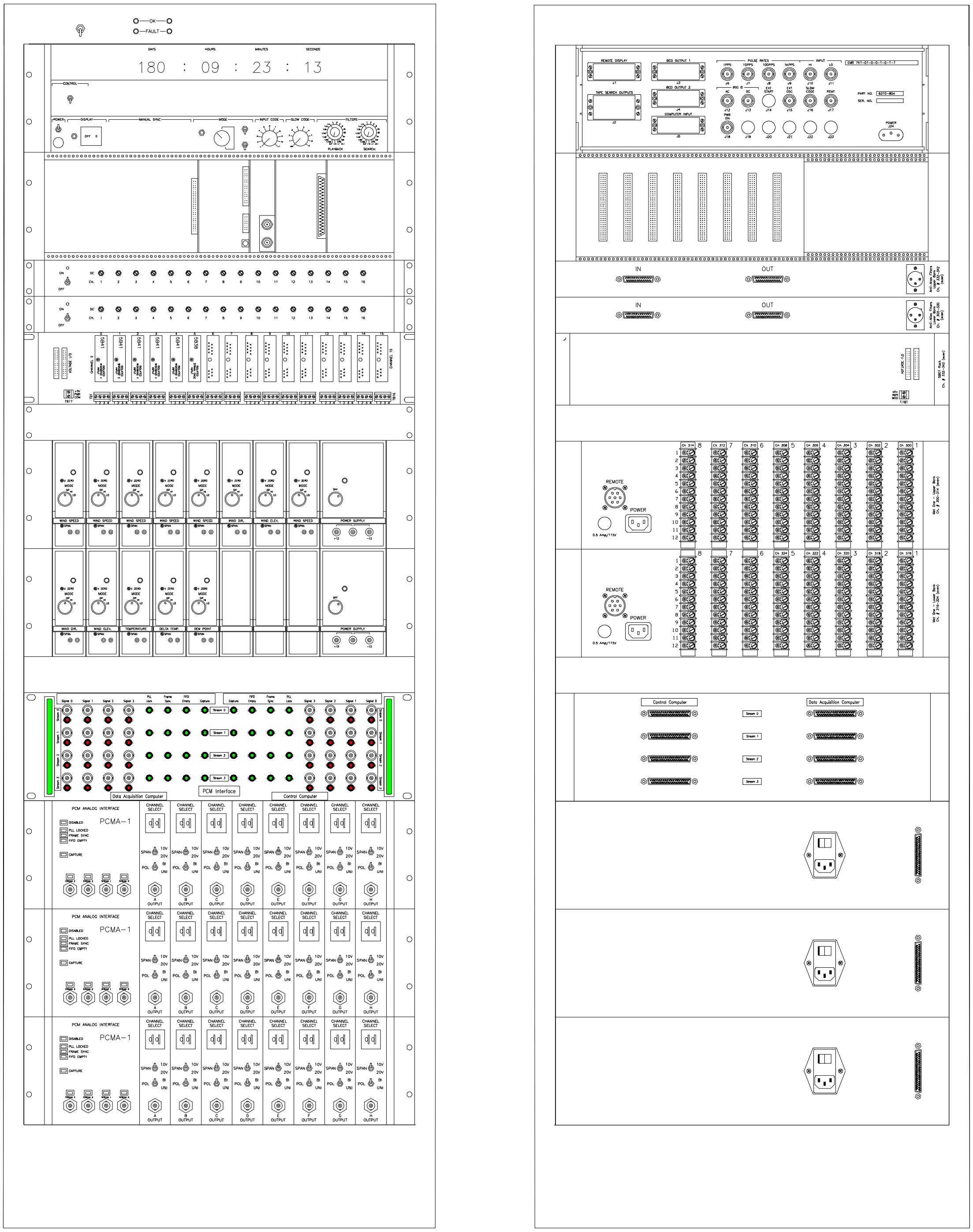


Figure 50. Ground-based PCM rack, front view and rear view

Data Storage, Processing, and Real-time Display

Data Collection and Storage

1. Complete calibrations, and build *master.hdr*. If there is no new calibration data, use the current *master.hdr* file.
2. Allow turbine to run at least five minutes before initiating data collection procedure. This allows temperature variations on the blades to stabilize.
3. Run *go.bat* [go filename(no extension)]. The following procedures are contained in this batch file:
    a. Initiate pressure calibration sequence (*psc.exe*) or use post-calibration from the previous campaign depending upon user selection.
    b. Update *master.hdr* with new pressure calibration coefficients (*hupdate.exe*).
    c. Record 10 minutes of data to optical disk under filename specified when calling the batch file (*collect.exe*).
    d. Initiate pressure post-calibration (*psc.exe*).
    e. Copy all calibration files and collection files to optical disk.

Data Post-Processing

1. Run *MUNCH.EXE* to convert raw PCM data to engineering units and calculate derived channels.
2. Write CD-ROM using the following file structure:
    CALIB\ (contains all programs and files related to calibrations)
    COLLECT\ (contains all programs and files related to data collection)
    PROCESS\ (contains all processing input files)
    **.arc* (archive file)
    **.dat* (raw binary data file)
    **.eng* (binary engineering-unit file)
    **.hd1* (header file listing each channel, calibration coefficients, and statistics).

Other Post-Processing Options

1. View data graphically (*viewdisk.exe*).
2. Extract data subsets (*pdis.exe*).
3. Compare pre- and post-calibrations of pressure channels (*drift.exe*).
4. Average each channel over a complete revolution of instrumented blade (*cycstat.exe*).
5. Select cycles based on user specified range or specified criteria (*eventloc.exe*).
6. Select cycles based on dynamic stall conditions (*dstall.exe*).
7. Extract time series of specified cycles (*scrunch.exe*).

Data Real-Time Display

1. View data graphically (*viewall.exe*).
2. Video overlay with data (*view.exe*).
3. Bar graph showing all four PCM streams (*barsall.exe*).
4. Single bar chart (*onebar.exe*).
5. Time-averaged series of user specified channel (*strip.exe*).

Note: The nitrogen tank pressure channel (213) may be observed using *barsall.exe*, *onebar.exe*, or *strip.exe*. This channel is not recorded in the **.dat* file which is necessary for all further processing.

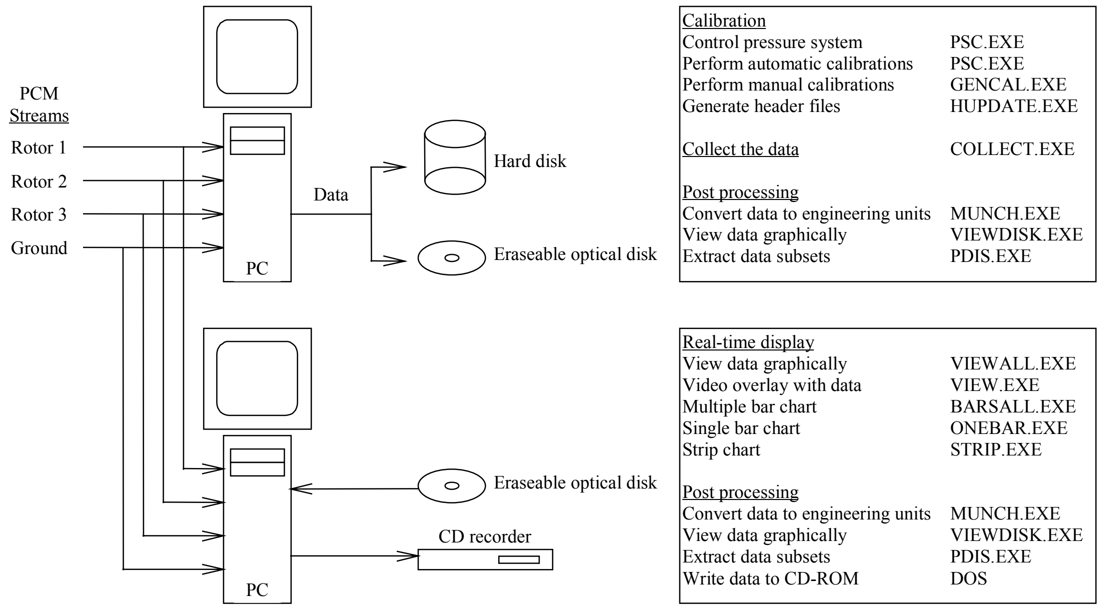


Figure 51. Signal path from PCM streams to useable data

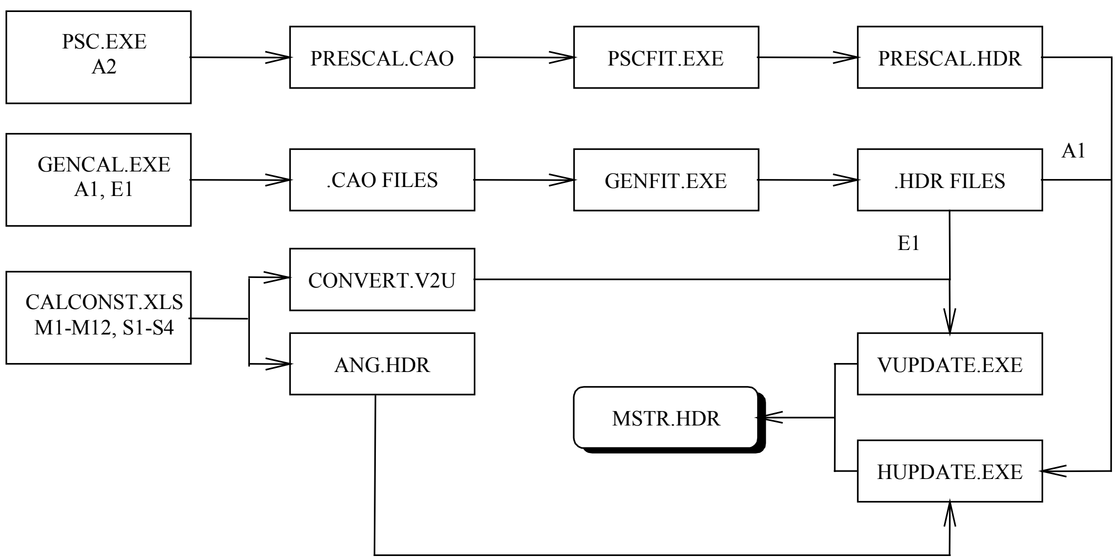


Figure 52. Production of calibration and header files (calibration procedures are summarized on p. 111)

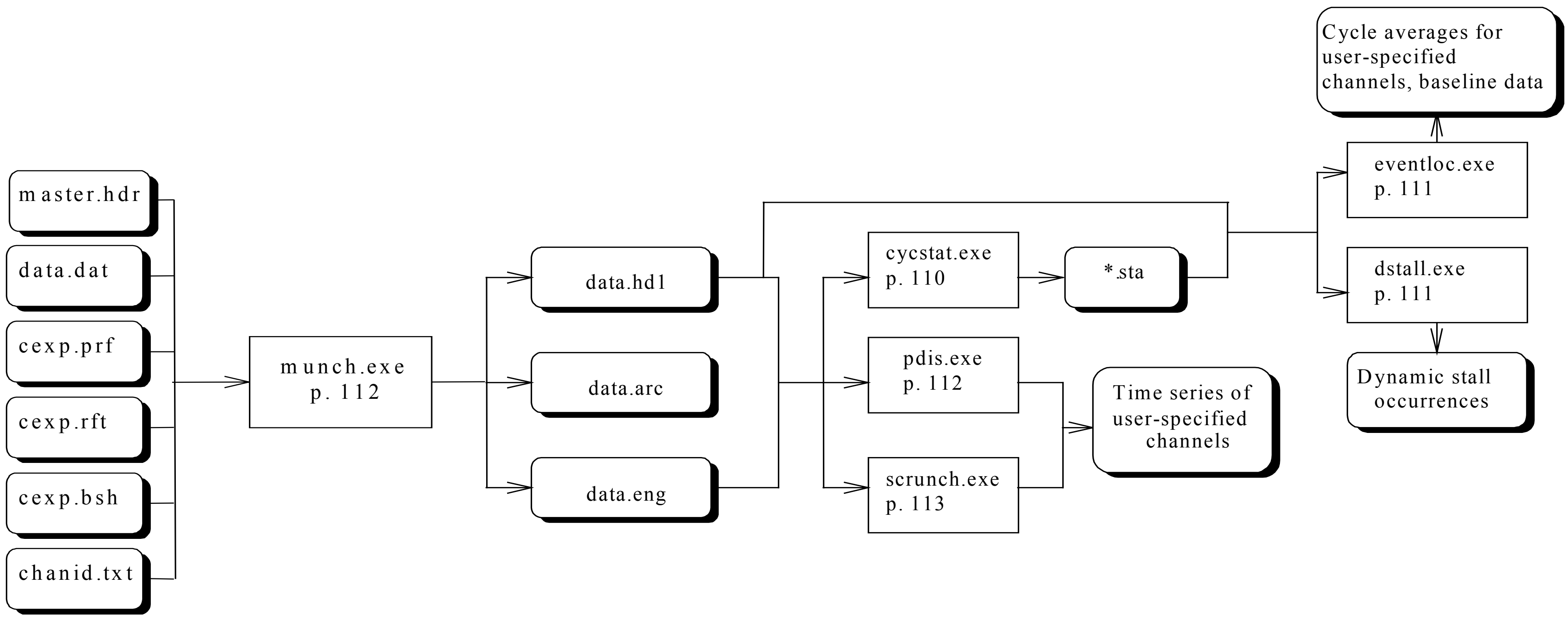


Figure 53. Data processing flow chart

Applied Load Calibration - (A1-A4)

The pressure transducers, the strain gauges, and the load cells were calibrated using this method. Known loads were applied and the results recorded in **.cao* files. Linear regression provided slopes, and the offsets were determined under zero-load conditions. These values are stored in temporary header files, **.hdr*. The *buildhdr.bat* process incorporates these values in the *master.hdr* file.

Table 23. Strain Gauge Calibration File Names

Channel Number	ID Code	File Name*	Calibration Range	Increment
225	B1RFB	*b1fpu.cao, b1fnu.cao* *b1fpd.cao, b1fnd.cao*	0 – 100 lb 100 – 0 lb	20 lb
227, 241	B1REB, HSTQ1, HSTQ2, LSSTQ	*b1epu.cao, b1enu.cao* *b1epd.cao, b1end.cao*	0 – 100 lb 100 – 0 lb	20 lb
233, 237	B3RFB	*b3fpu.cao, b3fnu.cao* *b3fpd.cao, b3fnd.cao*	0 – 100 lb 100 – 0 lb	20 lb
235, 241	B3REB, HSTQ1, HSTQ2, LSSTQ	*b3epu.cao, b3enu.cao* *b3epd.cao, b3end.cao*	0 – 100 lb 100 – 0 lb	20 lb
215, 217, 237, 239	HSXXB, HSYYB, LSSXXB, LSSYYB	*hsxxpu.cao, hsxxnu.cao,* *hsxxpd.cao, hsxxnd.cao,* *lssxxpu.cao, lssxxnu.cao,* *lssxxpd.cao, lssxxnd.cao* *Similarly for hsyy, lssyy.*	0 – 100 lb 100 – 0 lb	20 lb
342	NAYM	*b3ympu.cao, b3ymnu.cao,* *b3ympd.cao, b3ymnd.cao*	0 – 100 lb 100 – 0 lb	20 lb
225, 227, 233, 235, 237, 239, 241	B1RFB, B1REB, B3RFB, B3REB, HSXXB, HSYYB, HSTQ1, HSTQ2, LSSXXB, LSSYYB, LSSTQ	*zerox000.cao, zerox030.cao,* *zerox060.cao, zerox090.cao,* *zerox120.cao, zerox150.cao,* *zerox180.cao, zerox210.cao,* *zerox240.cao, zerox270.cao,* *zerox300.cao, zerox330.cao*	0 – 330°	30°

* p indicates load in positive direction; n indicates load in negative direction; u indicates increasing load; d indicates decreasing load; zerox = zero1 or zero2: because *gencal* is limited to 8 channels; the channels were split in two files for the zero offset determination.

Manufacturer Specifications - (M1-M13)

Calibrations of the instruments were performed by the manufacturer according to accepted practices. The resulting slope and offset values were entered in *calconst.xls*. The macros *Write ang.hdr* and *Write convert.v2u* convert the information in the Excel spreadsheet to text file formats. Using the *buildhdr.bat* batch file, these values were then combined with the results from the electronic path calibration to producethe slope and offset values stored in *master.hdr*.

Single-Point Offset Determination - (S1-S6)

Each transducer was oriented with a known position using a jig or by line of sight. The associated count value was recorded in *calconst.xls*. The equation of the line for the manufacturer-supplied slope and the manually determined offset was found. These slope and offset values were transferred to *ang.hdr* in the case of the digital channels, and the analog channel calibration coefficients were combined with the electronic path calibration coefficients using *vupdate.exe*. The *buildhdr.bat* batch file then collected all of this information in the *master.hdr* file.

Electronic Path Calibration - (E1)

All of the meteorological instruments, the accelerometers, the barometric pressure transducer and the power transducer use data provided by the manufacturer due to off-site calibrations. The electronic path used by each of these devices is then calibrated by injecting voltages and determining slope and offset values. The precision voltage generator is inserted in the electronic path as near the transducer as possible. The *gc.bat* batch file uses *gencal.exe* to collect 500 samples at 520.83 Hz at each voltage level specified by the user. The *genfit.exe* program performs a linear curve fit and outputs slope and offset values in **.hdr* files. The files are used during the *buildhdr.bat* process to convert manufacturer-supplied calibration coefficients to units of engineering unit/count. The voltage ranges for the various transducers are listed below.

Table 24. Electronic Path Calibration File Names and Voltage Ranges

Channel Number	ID Code	File Name	Calibration Range	Voltage Increment
334	BARO	*Baro.cao*	0.0-4.5 V	0.5 V
201, 203, 205, 207, 209, 211	B1ACFL, B1ACED, B2ACFL, B2ACED, B3ACFL, B3ACED	*Bladeacl.cao*	-0.8-0.8 V	0.2 V
336, 338, 340	NAACYW, NAACFA, NAACPI	*Grndacl.cao*	-0.9-0.9 V	0.2 V
300, 302, 304, 306, 308, 310, 312, 314	LMWS24M, LMWS17M, LMWS10M, LMWS2M, NLMWS17M, NLMWD17M, NLMWE17M, SLMWS17M	*Ground1.cao*	0.0-4.5 V	0.5 V
316, 318, 320, 322, 324	SLMWD17M, SLMWE17M, LMT2M, LMDT, LMDP2M	*Ground2.cao*	0.0-4.5 V	0.5 V
332	GENPOW	*Power.cao*	-4.5-4.5 V	1.0 V
326, 328, 330	LMSU17M, LMSV17M, LMSW17M	*Sonic.cao*	-4.5-4.5 V	1.0 V

Master Header File Compilation (*buildhdr.bat*)

Once each of the above calibration sequences is completed, the *master.hdr* file containing slope and offset values for every channel is created. Macros (*Write ang.hdr* and *Write convert.v2u*) in *calconst.xls* create text files in the same format as the **.hdr* files output by *genfit.exe*. These two files, *ang.hdr* and *convert.v2u*, contain the slope and offset values that were stored in *calconst.xls*. The *buildhdr.bat* batch file then compiles all of the calibration coefficients from the manufacturer, the electronic path calibration, and applied load calibrations into one file that is input in the post-processing software, *munch*. The program *vupdate.exe* converts the manufacturer data in *convert.v2u* from units of engineering unit/volt to engineering unit/count using information in the **.hdr* files from the electronics calibrations. These new values are stored in *master.hdr*. Calibration coefficients for the digital position encoders, pressure channels, and strain gauges are transferred, using *vupdate.exe*, from their respective **.hdr* files to the master header file, *master.hdr*.

Other Calibrations

Angle Star

The zero was determined by placing the Angle Star on a machinist's surface plate. The surface plate was leveled with a machinist's level accurate to 0.0005 in/ft. The slope was determined by placing the device on precision ground angles on the surface plate at 5°, 10°, 15°, 20°, and 30°. The Angle Star was adjusted until the proper readings were attained. This was done prior to the pitch system calibration.

Pitch System

Each blade was pitched to 0°. The Angle Star was attached to a jig that fit around the leading and trailing edge of the airfoil at the tip. The jig was moved from the upwind side to the downwind side of the airfoil for comparison of the angle measurement. The Angle Star provided the known pitch angle of the blade relative to the ground. The offset value in *calconst.xls* was adjusted until the data system produced the same value as the Angle Star. This was done for both blades.

The nacelle tilt angle was determined by placing the Angle Star on machined surfaces parallel to the ground. Angles were recorded at five locations, and the average value is the nacelle tilt, 1°. Positive nacelle tilt indicates that the boom tip is higher than the upwind side of the low-speed shaft. The blade pitch angle offset values were then adjusted to account for this tilt angle.

Precision Voltage Generator

Two devices are available for use during the electronic path calibrations. The HP 3245A Universal Source was calibrated by the manufacturer on 7/10/90. The Fluke 743B Documenting Process Calibrator was calibrated by the manufacturer on 7/31/97.

Scale

Two scales were used to weigh the blades, and they were calibrated with known weights prior to weighing the blades. One scale was used on the root end of the blade, and the other scale was used on the tip end of the blade. The combined reading provided the total weight of the blade.

Processing Program Summary

bar.exe	Input: **.cfg, *.cap, *.stm, master.hdr*, # of desired PCM stream Output: none Description: One of the PCM streams is selected, and a horizontal bar chart displays each of the channels on that stream. The spacebar highlights a particular channel, and it's count value and engineering unit value is displayed at the bottom of the screen. This program is useful during calibration of the digital position encoders and observing Ni tank pressure and digital reference pressure channels. This program is written in C.
bars.exe	Input: **.cap, *.cfg, *.stm* Output: None Description: Bar graphs display each of the four PCM streams in real time. This is a useful program for determining if a channel is railed or not operating. This program was written in C.
calconst.xls	Input: Manufacturer supplied slope and offset values, and single-point offsets Output: *ang.hdr*, *convert.v2u* Description: This spreadsheet contains all manufacturer specified slope and offset values. The single-point offsets determined during calibration are also inserted in the spreadsheet. The offset value is used in conjunction with the manufacturer specified slope to determine the equation of the line representing each sensor. Two macros are run to create two files that contain slope and offset values in the format output by *genfit.exe* (**.hdr*). The calibration coefficients for the digital channels that measure angles are contained in *ang.hdr*, and all of the other calibration coefficients are contained in *convert.v2u*.
collect.exe	Input: **.cap, *.cfg, *.stm* Output: **.dat* Description: Decoded PCM data is stored directly to erasable optical disk. This program is written in C.
cycstat.exe	Input: List of disk names, input pathname, output pathname Output: **.sta* Description: The mean, maximum, minimum, and standard deviation is determined for each channel over each complete revolution of the instrumented blade. The azimuth angle at the maximum value, the azimuth angle at the minimum value, the wind speed at the minimum value, and the yaw error angle at the minimum value are also recorded. A database is created consisting of one **.sta* file for each 10-minute campaign. This program is written in FORTRAN.
drift.exe	Input: **.cao* (Both the pre- and post-calibration files are required.) Output: *drift.txt* Description: A comparison between pre- and post-calibration of pressure transducers is done. The maximum and minimum drift for each pressure channel is recorded. The maximum and minimum drift overall is also recorded. This program is written in C.

dstall.exe

Input: List of disk names, **.sta* files, **.hd1* files
Output: User specified file names
Description: The user initially specifies which span location (or all span locations) to analyze. The program reads the leading edge pressure coefficients, minimum wind speed, and minimum yaw error values from the **.sta* files. The user is then prompted to limit the data by C_p magnitude, span location, wind velocity, yaw error angle, or azimuth angle. Once data is selected, the user may see the number of cycles remaining, or the cycles with dynamic stall occurring at more than one span location. The data may then be binned or sorted and written to a user specified file. This program is written in FORTRAN.

eventloc.exe

Input: list of disk names or list of specific cycles, input pathname, output pathname, **.sta* files, **.hd1* files.
Output: user specified file names
Description: The user may choose from three options to extract cycle-averaged values. This program is written in FORTRAN.

1. Cycles may be selected based on inflow criteria such as wind speed, yaw error angle, wind shear, etc. Cycles may be analyzed in groups or as single cycles. A user-specified file consisting of ranges of cycles meeting the specified criteria and the values associated with those cycles (i.e., average wind speed) is output. Additionally, a file with the user-specified name and a **.nam* extension is output. This file lists the disk name and median cycle of the specified range. This file may be input to option 2.
2. The user may specify a file containing a list of disk names and cycle numbers that was created in option 1 (**.nam*). The user is then prompted for the desired channels corresponding to these cycles. Options include aerodynamic force coefficients, inflow conditions, channels related to calculations of dynamic pressure, power-related channels or a user specified list of channels. The user then specifies the output file name.
3. This option produces the same type of output as option 2, but the user specifies a range of cycles common to all user specified disks. Again, the output file is specified by the user.

gencal.exe

Input: *gencal.cap, vbl.lst*
Output: **.cao*
Description: This program was developed to automate sample collection. All of the strain gauge and electronic path calibrations are performed using this software (Scott, Unpublished). This program is written in C.

1. Create *gencal.exe* input file (**.cao*) by copying the channel(s) to be calibrated from *vbl.lst* to the new input file. Ensure the first line indicates the number of channels in the file, and the appropriate PCM stream is listed in *gencal.cap*.
2. Apply load or voltage and collect samples according to user key-stroke input. The software is hardwired to collect 20 samples at 520 Hz when the user signals beginning of collection.
3. Repeat until samples are collected up to 20 desired load or voltage conditions. This can be done until the user exits the data collection portion of the program. The **.cao*input file is modified to contain the x and y values created using this program.

genfit.exe	Input: **.cao* (with modifications from *gencal.exe*) Output: **.hdr, *.rpt, *.res* Description: This program was developed to perform a linear-regression analysis on samples collected using *gencal.exe*. All of the strain gauge and electronic path calibrations are performed using this software. The resulting slopes and offsets are recorded in **.hdr* according to the channels contained in the input file (Scott Unpublished). This program was written in C.
go.bat	Input: user specified filename of data to be collected (i.e., go d403001) Description: This batch file initiates calibration of the pressure transducers, updates *master.hdr* with the new pressure channel slope and offset values, collects 10 minutes of data, and initiates a post-calibration of the pressure transducers.
hupdate.exe	Input: **.hdr* files corresponding to channels with calibration coefficients in units of engineering unit/count and counts. Output: **.hdr* updated Description: The slope and offset calibration coefficients are transferred from **.hdr* files to *master.hdr*. This program is written in C.
munch.exe	Input: **.hdr*, **.dat, cexp.rft, cexp.bsh, cexp.prf, *.stp, chanid.txt*, *s1pit.tbl, s1tpsph.tbl, s1yaw.tbl…s5pit.tbl, s5tpsph.tbl, s5yaw.tbl.* Output: **.hd1, *.arc, *.eng, pdiserr.log* Description: Raw PCM data is converted to engineering units using the calibration coefficients listed in *master.hdr*. In addition to the measured channels, several derived channels are calculated. These include aerodynamic force coefficients, upwash corrected angles of attack, normalized pressure coefficients, and stagnation point pressures. Formulae describing each of these calculations are described in the final report. The output file, **.hd1*, contains the mean, maximum, minimum, and standard deviation of each channel over the 10-minute campaign. One output file, **.arc*, is an archive file essentially copying **.dat*, and the engineering unit conversions are stored in **.eng*. Any errors encountered during processing are indicated in *pdiserr.log*. The additional input files provide information about the record format (*cexp.rft*), blade shape (*cexp.bsh*), pressure profiles (*cexp.prf*), 8-letter codes corresponding to each channel (*chanid.txt*), and look-up tables for each of the 5-hole probes (*s1pit.tbl, s1tpsph.tbl, s1yaw.tbl…s5pit.tbl, s5tpsph.tbl, s5yaw.tbl*). These file formats are discussed in the program's documentation (Scott Unpublished). This program is written in C.
pdis.exe	Input: **.eng*, **.hd1* Output: **.hd2, *.en2* Description: The user may select specific channels and specific frame numbers to be extracted. A new header file is created consisting only of the selected channels, and another file contains all of the selected data. This program is written in C.
psc.exe	Input: *rampcal.cai* Output: *prescal.cao* Description: The syringe is used to apply pressures to each of the transducers according to the ramp values indicated in *rampcal.cai*. The

count value associated with each applied pressure is recorded to the *prescal.cao* file. This program is written in C.

pscfit.exe	Input: *prescal.cao, t2c.dat* Output: *prescal.hdr, prescal.res, prescal.rpt* Description: A linear-regression analysis is performed using the applied pressures and associated count values resulting from *psc.exe*. A slope and offset is determined for each channel at each transducer. These slopes and offsets are recorded in *prescal.hdr*. The file *t2c.dat* provides correlation between transducer tap numbers and pressure channel numbers. This program is written in C.
scrunch.exe	Input: channel list file, **.eng* file, **.hd1* file Output: user specified file name Description: This program writes the time series values for a user-specified range of consecutive cycles. The channels are listed in a file specified by the user. This program is written in FORTRAN.
strip.exe	Input: *chanfile.txt, master.hdr* Output: none Description: User-specified channels are displayed as a moving time average. The time interval is specified by the user. This program is generally left running overnight to get a feel for the wind speed variations or for diagnostic purposes. This program is written in C.
view.exe	Input: *master.hdr*, **.cfg, *.cap, *.stm*, incoming decoded PCM streams Output: none Description: The graphical depiction of measured values provided by *viewall.exe* is overlaid on video pictures. The screen may be split to show views from two cameras. Any of the four cameras may be selected (boom camera, blade camera, shed camera, or tower camera). This program is written in C.
viewall.exe	Input: *master.hdr*, **.cfg, *.cap, *.stm*, incoming decoded PCM streams Output: none Description: A graphical depiction of various channels is displayed in real time. Pressure distributions for each span location are displayed on the left. The instrumented blade azimuth angle and rotational speed are included. Wind speeds are shown on a vertical graph to provide a visual indication of vertical wind shear. Horizontal wind shear is depicted similarly. Wind direction is shown in relation to turbine angle to provide an indication of yaw error. Other values such as time, temperature, and blade pitch angle are presented as text at the top of the screen. This program is written in C.
vieweng.exe	Input: **.eng*, **.hd1* Output: none Description: A previously recorded campaign is displayed graphically in the same format as the real-time software *viewall.exe*. The user may speed up or slow down the display or jump to a specific frame number. This program is written in C.
vupdate.exe	Input: *convert.v2u*, **.hdr* files corresponding to electronic path calibrations. Output: **.hdr* Description: All of the slope and offset values that were stored in *calconst.xls* are contained in the text file *convert.v2u*, and the slopes are

in units of engineering unit/volt. The electronic path calibrations performed using *gencal.exe* and *genfit.exe* produced slope and offset coefficients in units of volts/count for the electronic pathways. This program converts the calibration coefficients to units of engineering unit/count, and these values are recorded in **.hdr*. This program is written in C.

File Format Examples

ang.hdr contains the manufacturer-supplied slope and single-point offsets for the position encoders. This file is created by the macro *Write ang.hdr* in the spreadsheet *calconst.xls*. The first line indicates the number of channels contained in the file. The following lines list the channel number, description, units, number of calibration coefficients, offset, slope, and other values consistent with the format specified by Scott (unpublished).

```
6
349,"Azimuth","deg",2,-110.126953125,.087890625,0,0,0,0,-99999,99999,0,"M"
351,"Yaw","deg",2,218.435546875,.087890625,0,0,0,0,-99999,99999,0,"M"
251,"Flap 1","deg",2,32.40966796875,-.010986328125,0,0,0,0,-99999,99999,0,"M"
253,"Pitch 1","deg",2,-20.0390625,.087890625,0,0,0,0,-99999,99999,0,"M"
255,"Flap 3","deg",2,19.599609375,-.010986328125,0,0,0,0,-99999,99999,0,"M"
257,"Pitch 3","deg",2,-21.884765625,.087890625,0,0,0,0,-99999,99999,0,"M"
```

calconst.xls is a spreadsheet containing all of the manufacturer-supplied slope and offset values. The offsets determined by the single-point offset calibration are also entered in this spreadsheet.

Name	Single point			Slope		Coefficients			Channel	Units
Azimuth	180°=	795	counts	0.087890625	° / count	-110.1269531	0.087890625	*counts	349	deg
Yaw	292°=	837	counts	0.087890625	° / count	218.4355469	0.087890625	*counts	351	deg
Flap 1	0°=	2950	counts	-0.01098633	° / count	32.40966797	-0.01098633	*counts	251	deg
Pitch 1	0°=	228	counts	0.087890625	° / count	-20.0390625	0.087890625	*counts	253	deg
Flap 3	0°=	1784	counts	-0.01098633	° / count	19.59960938	-0.01098633	*counts	255	deg
Pitch 3	0°=	249	counts	0.087890625	° / count	-21.88476563	0.087890625	*counts	257	deg
Windspeed - 80'	0 m/s=	0	volts	10	m/s / V	0	10	*volts	300	mps
Windspeed - 56'	0 m/s=	0	volts	10	m/s / V	0	10	*volts	302	mps
Windspeed - 33'	0 m/s=	0	volts	10	m/s / V	0	10	*volts	304	mps
Windspeed - 8'	0 m/s=	0	volts	10	m/s / V	0	10	*volts	306	mps
Windspeed - N	0 m/s=	0	volts	10	m/s / V	0	10	*volts	308	mps
Windspeed - S	0 m/s=	0	volts	10	m/s / V	0	10	*volts	314	mps
Wind direction - N	292°=	2.594	volts	72	° / V	105.232	72	*volts	310	deg
Wind direction - S	292°=	2.594	volts	72	° / V	105.232	72	*volts	316	deg
Wind elevation - N	0°=	2.465	volts	-24.0021122	° / V	59.15320548	-24.0021122	*volts	312	deg
Wind elevation - S	0°=	2.376	volts	-23.9973603	° / V	57.01772805	-23.9973603	*volts	318	deg
Delta Temperature	0°=	2	volts	2.22222222	°C / V	-4.44444444	2.22222222	*volts	322	degC
Temperature - 8'	0°=	2.5	volts	20	°C / V	-50	20	*volts	320	degC
Dew point	0°=	2.5	volts	20	°C / V	-50	20	*volts	324	degC
Sonic U	0 m/s=	0	volts	10	m/s / V	0	10	*volts	326	mps
Sonic V	0 m/s=	0	volts	10	m/s / V	0	10	*volts	328	mps
Sonic W	0 m/s=	0	volts	3	m/s / V	0	3	*volts	330	mps
Barometer	74000 Pa=	0	volts	5200	mBar / V	74000	5200	*volts	334	Pascal
Generator power	0 kW=	0	volts	8	kW / V	0	8	*volts	332	kW
Blade 1 Flap Accel	0 g=	0	volts	199	mV/g	0	49.24623116	*volts	201	mps2
Blade 1 Edge Accel	0 g=	0	volts	198.7	mV/g	0	49.32058379	*volts	203	mps2
Blade 3 Flap Accel	0 g=	0	volts	201	mV/g	0	48.75621891	*volts	209	mps2
Blade 3 Edge Accel	0 g=	0	volts	200.7	mV/g	0	48.82909816	*volts	211	mps2
Nacelle Yaw Accel	0 g=	0	volts	199.9	mV/g	0	49.02451226	*volts	336	mps2
Nacelle Fore-Aft Accel	0 g=	0	volts	200.9	mV/g	0	48.7804878	*volts	338	mps3
Nacelle Pitch Accel	0 g=	0	volts	201	mV/g	0	48.75621891	*volts	340	mps2

convert.v2u contains the manufacturer-supplied slope and offsets in units of e.u./V and V, respectively. This file is created by the macro *Write convert.v2u* in the spreadsheet *calconst.xls*. The first line indicates the number of channels contained in the file. The following lines list the channel number, description, units, number of calibration coefficients, offset, and slope.

```
25
```

```
300,"Windspeed - 80'","mps",2,0,10
302,"Windspeed - 56'","mps",2,0,10
304,"Windspeed - 33'","mps",2,0,10
306,"Windspeed - 8'","mps",2,0,10
308,"Windspeed - N","mps",2,0,10
314,"Windspeed - S","mps",2,0,10
310,"Wind direction - N","deg",2,105.232,72
316,"Wind direction - S","deg",2,105.232,72
312,"Wind elevation - N","deg",2,59.1532054820824,-24.0021121858724
318,"Wind elevation - S","deg",2,57.0177280499145,-23.9973602903681
322,"Delta Temperature","degC",2,-4.44444444,2.22222222
320,"Temperature - 8'","degC",2,-50,20
324,"Dew point","degC",2,-50,20
326,"Sonic U","mps",2,0,10
328,"Sonic V","mps",2,0,10
330,"Sonic W","mps",2,0,3
334,"Barometer","Pascal",2,74000,5200
332,"Generator power","kW",2,0,8
201,"Blade 1 Flap Accel","mps2",2,0,49.2462311557789
203,"Blade 1 Edge Accel","mps2",2,0,49.3205837946653
209,"Blade 3 Flap Accel","mps2",2,0,48.7562189054726
211,"Blade 3 Edge Accel","mps2",2,0,48.8290981564524
336,"Nacelle Yaw Accel","mps2",2,0,49.0245122561281
338,"Nacelle Fore-Aft Accel","mps3",2,0,48.7804878048781
340,"Nacelle Pitch Accel","mps2",2,0,48.7562189054726
```

gencal.cap contains the PCM stream capture information necessary for *gencal.exe* to obtain the required channels. For the channels specified in a given *.cao file, the corresponding PCM stream must be specified in the line 'USE SIGNAL *;'.

```
CAPTURE INFORMATION:
  CARD 0:
    SIGNAL 0 = PCM STREAM 4;
    SIGNAL 1 = PCM STREAM 4;
    SIGNAL 2 = PCM STREAM 4;
    SIGNAL 3 = PCM STREAM 4;
    USE SIGNAL 3;
    CAPTURE CHANNELS 1-62;
```

ground2.cao is an example of the file input to *gencal*. This file was used to calibrate the electronic path for several of the ground-based meteorological channels. The first line indicates the number of channels contained in the file. The following lines are copied from *vbl.lst*. The line of text containing a date begins the modification that occurs when *gencal* is run. The following x,y coordinates were obtained on the date specified. The first two columns correspond to voltages injected and count values read from the "South wind direction" channel. The next two columns correspond to the "South wind elevation" channel, etc.

```
NV 5
9,016,"Vbl 9","South wind direction 17.02m","V",1,"M",0.000000, 1.000000
10,018,"Vbl 10","South wind elevation 17.02m","V",1,"M",0.000000,1.000000
11,020,"Vbl 11","Local met temperature 2.44m","V",1,"M",0.000000,1.000000
12,022,"Vbl 12","Delta temperature","V",1,"M",0.000000,1.000000
13,024,"Vbl 13","Local met dewpoint 2.44m","V",1,"M",0.000000,1.000000
Fri Apr 18 10:54:20 1997
  0.000 2047   0.000 2047   0.000 2047   0.000 2048   0.000 2044
  0.000 2047   0.000 2047   0.000 2047   0.000 2048   0.000 2044
  0.500 1844   0.500 1843   0.500 1843   0.500 1844   0.500 1841
  0.500 1844   0.500 1843   0.500 1843   0.500 1844   0.500 1841
  1.000 1641   1.000 1638   1.000 1640   1.000 1640   1.000 1637
```

```
 1.000 1641   1.000 1639   1.000 1640   1.000 1640   1.000 1637
 1.500 1437   1.500 1434   1.500 1436   1.500 1436   1.500 1434
 1.500 1437   1.500 1434   1.500 1436   1.500 1436   1.500 1434
 2.000 1233   2.000 1230   2.000 1233   2.000 1232   2.000 1230
 2.000 1234   2.000 1230   2.000 1233   2.000 1232   2.000 1230
 2.500 1030   2.500 1026   2.500 1029   2.500 1028   2.500 1027
 2.500 1030   2.500 1026   2.500 1029   2.500 1028   2.500 1026
 3.000  827   3.000  821   3.000  825   3.000  824   3.000  823
 3.000  827   3.000  821   3.000  825   3.000  824   3.000  823
 3.500  623   3.500  617   3.500  622   3.500  620   3.500  620
 3.500  623   3.500  617   3.500  622   3.500  620   3.500  619
 4.000  420   4.000  412   4.000  418   4.000  416   4.000  416
 4.000  420   4.000  412   4.000  418   4.000  416   4.000  416
 4.500  216   4.500  208   4.500  214   4.500  212   4.500  213
 4.500  216   4.500  208   4.500  215   4.500  212   4.500  213
```

ground2.hdr is an example of the file output from *genfit*. A linear regression was performed on the data added to *ground2.cao* during the *gencal* program. The resulting slope and offset are inserted in the appropriate locations of the **.hdr* file. This file is then used together with *convert.v2u* during the *vupdate* program to create the *master.hdr* file.

```
005
316,"South wind direction 17.02m","V",2,5.0315e+000,-2.4575e-003,,,,0,0,0,0,"M"
318,"South wind elevation 17.02m","V",2,5.0091e+000,-2.4467e-003,,,,0,0,0,0,"M"
320,"Local met temperature 2.44m","V",2,5.0268e+000,-2.4558e-003,,,,0,0,0,0,"M"
322,"Delta temperature","V",2,5.0196e+000,-2.4510e-003,,,,0,0,0,0,"M"
324,"Local met dewpoint 2.44m","V",2,5.0224e+000,-2.4570e-003,,,,0,0,0,0,"M"
```

master.hdr is a portion of the file containing all calibration coefficients. This file is input to the *munch* processing software. The first line indicates the number of lines of text in the file, and each channel is represented with text on one line. Each line consists of the channel number, description, units, number of calibration coefficients, offset, slope, and dummy values for the mean, maximum, minimum, and standard deviation. The last entry indicates the type of measurement (Scott, unpublished).

```
201
000,"Pressure #1, 30% span, trailing ","Pascal",2,-
2808.899902,1.397400,,,,0.000000,-999999.000000,999999.000000,0.000000,"M"
001,"Pressure #1, 47% span, trailing ","Pascal",2,-
2723.100098,1.411000,,,,0.000000,-999999.000000,999999.000000,0.000000,"M"
002,"Pressure #4, 30% span, 80% upper ","Pascal",2,-
2786.600098,1.398900,,,,0.000000,-999999.000000,999999.000000,0.000000,"M"
003,"Pressure #4, 47% span, 80% upper ","Pascal",2,-
2724.699951,1.460000,,,,0.000000,-999999.000000,999999.000000,0.000000,"M"
004,"Pressure #6, 30% span, 68% upper ","Pascal",2,-
2689.600098,1.389400,,,,0.000000,-999999.000000,999999.000000,0.000000,"M"
005,"Pressure #6, 47% span, 68% upper ","Pascal",2,-
2850.000000,1.440600,,,,0.000000,-999999.000000,999999.000000,0.000000,"M"
006,"Pressure #8, 30% span, 56% upper ","Pascal",2,-
2687.300049,1.416400,,,,0.000000,-999999.000000,999999.000000,0.000000,"M"
007,"Pressure #8, 47% span, 56% upper ","Pascal",2,-
2906.000000,1.449700,,,,0.000000,-999999.000000,999999.000000,0.000000,"M"
008,"Pressure #11, 30% span, 36% upper ","Pascal",2,-
2764.500000,1.410900,,,,0.000000,-999999.000000,999999.000000,0.000000,"M"
009,"Pressure #11, 47% span, 36% upper ","Pascal",2,-
3004.600098,1.465600,,,,0.000000,-999999.000000,999999.000000,0.000000,"M"
```

.hd1 is a portion of the header file produced by the post-processing software, *munch*. This file contains statistics for the 10-minute campaign. The second line lists the number of channels, the number of records in the corresponding **.eng* file, and the time step between records. Next, each channel is represented by one line of text beginning with the channel number. The channel description, units, number of calibration coefficients, offset, slope, mean, maximum, minimum, and standard deviation follow. The last entries are the channel type (Scott, unpublished), location of maximum, location of minimum, and number of frames in which an error occurred.

```
UAE-P3 HD1 FILE
269,312500,0.001920
000,"P0130100","Pressure #1, 30% span, trailing ","Pascal",2,-
2640.899902,1.347300,,,,0.572197,1.000000,-0.608794,0.127592,"M",779,179227,61
001,"P0147100","Pressure #1, 47% span, trailing ","Pascal",2,-
2513.600098,1.361300,,,,0.627824,1.000000,0.228395,0.137684,"M",822,168371,12117
3
002,"P043080U","Pressure #4, 30% span, 80% upper ","Pascal",2,-
2627.899902,1.347000,,,,0.401690,1.000000,-
0.921490,0.111137,"M",178450,151277,61
003,"P044780U","Pressure #4, 47% span, 80% upper ","Pascal",2,-
4057.899902,2.177200,,,,-0.935669,-0.242328,-
2.623565,0.460324,"M",17833,121131,121173
004,"P063068U","Pressure #6, 30% span, 68% upper ","Pascal",2,-
2519.699951,1.337900,,,,0.599029,1.000000,-1.569541,0.161127,"M",497,179193,61
```

***.eng** files contain the calibrated data parameters in engineering units along with all of the derived parameters. These binary files contain a series of 32-bit floating-point real numbers and one 8-bit byte for each frame of data. A 10-minute campaign consists of 312,500 records for 269 channels. Each line is one time step of 1.92 ms.

Channel 000	Channel 001	Channel 002	Channel 003	...	Channel 981	Error Byte
FLOAT	FLOAT	FLOAT	FLOAT	...	FLOAT	BYTE
FLOAT	FLOAT	FLOAT	FLOAT	...	FLOAT	BYTE
FLOAT	FLOAT	FLOAT	FLOAT	...	FLOAT	BYTE

...

***.sta** files contain the cycle-averaged values of each channel throughout the 10-minute campaign. The first cycle, 0, is the partial cycle at the beginning of the campaign. In addition to the mean values, the standard deviation, maximum, azimuth angle at the maximum, minimum, azimuth angle at the minimum, cup-average wind speed at the minimum value, and yaw error angle at the minimum are included. Additional "channels" are created and appended to the cycle-average record. The average wind speed of the cup-anemometers, excluding the one at 2m, is calculated. The yaw error angle based on the vector average of the two bi-vane anemometers and the turbine yaw angle is determined. Vertical and horizontal wind shears are calculated using the cup anemometers. Lastly, each record contains eight integer values representing the cumulative total per cycle of each bit of the eight-bit error byte. These files are stored in binary format.

Appendix C

Instrumentation Summaries

Table 25. Phase V Instrumentation Summary

Channel	ID Code	Description	Sensor Location	Measurement Type and Units	Sensor Type
000-050 (even)	Ptt30ccc Ptt36ccc Ptt41ccc	Surface pressures at 30%, 36%, and 41% span tt = transducer tap number ccc = %chord pressure tap location	Within blade 3 at approximately 30% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
052-060 (even)	5Hx34	5-hole probe at 34% span x = designation of hole in 5-hole probe	Within blade 3 at approximately 30% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
001-051 (odd)	Ptt47ccc Ptt52ccc Ptt58ccc	Surface pressures at 47%, 52%, and 58% span tt = transducer tap number ccc = %chord pressure tap location	Within blade 3 at approximately 47% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
053-061 (odd)	5Hx51	5-hole probe at 51% span x = designation of hole in 5-hole probe	Within blade 3 at approximately 47% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
100-150 (even)	Ptt63ccc Ptt69ccc Ptt74ccc	Surface pressure at 63%, 69%, and 74% span tt = transducer tap number ccc = % chord pressure tap location	Within blade 3 at approximately 63% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
152-160 (even)	5Hx67	5-hole probe at 67% span x = designation of hole in 5-hole probe	Within blade 3 at approximately 63% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
101-151 (odd)	Ptt80ccc Ptt85ccc Ptt90ccc	Surface pressures at 80%, 85%, and 90% span tt = transducer tap number ccc = % chord pressure tap location	Within blade 3 at approximately 80% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
153-161 (odd)	5Hx84	5-hole probe at 84% span x = designation of hole in 5-hole probe	Within blade 3 at approximately 80% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
200-250 (even)	Ptt95ccc Ptt92ccc Ptt98ccc	Surface pressures at 95%, 92%, and 98% span tt = transducer tap number ccc = % chord pressure tap location	Within blade 3 at approximately 95% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
252-260 (even)	5Hx91	5-hole probe at 91% span x = designation of hole in 5-hole probe	Within blade 3 at approximately 95% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
201	B1ACFL	Accelerometer Blade 1-Flap	Tip of blade 1	Linear flap acceleration, mps2	Accelerometer
203	B1ACED	Accelerometer Blade 1-Edge	Tip of blade 1	Linear edge acceleration, mps2	Accelerometer
209	B3ACFL	Accelerometer Blade 3-Flap	Tip of blade 3	Linear flap acceleration, mps2	Accelerometer
211	B3ACED	Accelerometer Blade 3-Edge	Tip of blade 3	Linear edge acceleration, mps2	Accelerometer
213	Not recorded	Analog Nitrogen tank pressure	Rotating instrumentation package	Pressure inside Ni tank, Pa	Pressure transducer
215	HSXXB	Strain HS XX Bending	Universal hub shaft	Bending moment, Nm	Strain gauge - 350 ohm
217	HSYYB	Strain HS YY Bending	Universal hub shaft	Bending moment, Nm	Strain gauge - 350 ohm
219	HSTQ1	Strain HS Torque 1	Universal hub shaft	Torque, Nm	Strain gauge - 350 ohm
221	HSTQ2	Strain HS Torque 2	Universal hub shaft	Torque, Nm	Strain gauge - 350 ohm
223	TLINKF	Strain Teeter link force	Rigid link between blades	Force, N	Tension and compression sensor

Table 25. Phase V Instrumentation Summary (continued)

Channel	ID Code	Description	Sensor Location	Measurement Type and Units	Sensor Type
225	B1RFB	Strain Blade 1 root flap bending	Blade 1 pitch shaft (8% span)	Bending moment, Nm	Strain gauge - 350 ohm
227	B1REB	Strain Blade 1 root edge bending	Blade 1 pitch shaft (8% span)	Bending moment, Nm	Strain gauge - 350 ohm
229	B1TDAMP	Strain Blade 1 teeter damper force	Blade 1 teeter damper	Force, N	Button force sensor
231	B3TDAMP	Strain Blade 3 teeter damper force	Blade 3 teeter damper	Force, N	Button force sensor
233	B3RFB	Strain Blade 3 root flap bending	Blade 3 pitch shaft (8% span)	Bending moment, Nm	Strain gauge - 350 ohm
235	B3REB	Strain Blade 3 root edge bending	Blade 3 pitch shaft (8% span)	Bending moment, Nm	Strain gauge - 350 ohm
237	LSSXXB	Strain X-X LSS bending	Low-speed shaft	Bending moment, Nm	Strain gauge - 350 ohm
239	LSSYYB	Strain Y-Y LSS bending	Low-speed shaft	Bending moment, Nm	Strain gauge - 350 ohm
241	LSSTQ	Strain LSS torque	Low-speed shaft	Torque, Nm	Strain gauge - 350 ohm
251	B1FLAP	Digital Blade 1 flap angle	Universal hub outboard of teeter bearing	Angular position, deg	Digital position encoder
253	B1PITCH	Digital Blade 1 pitch	Blade 1 root/hub attachment	Angular position, deg	Digital position encoder
255	B3FLAP	Digital Blade 3 flap angle	Universal hub outboard of teeter bearing	Angular position, deg	Digital position encoder
257	B3PITCH	Digital Blade 3 pitch	Blade 3 root/hub attachment	Angular position, deg	Digital position encoder
259, 261	VBL176 VBL178	Digital first 12 bits from Delta pressure, Digital last 12 bits from Delta pressure	Rotating instrumentation package	Reference pressure, 16 bit binary	Digital reference pressure
300	LMWS24M	Local met WS 24.38 m	Central MET Tower	Wind speed, m/s	Cup anemometer
302	LMWS17M	Local met WS 17.02 m (hub height)	Central MET Tower	Wind speed, m/s	Cup anemometer
304	LMWS10M	Local met WS 10.06 m	Central MET Tower	Wind speed, m/s	Cup anemometer
306	LMWS2M	Local met WS 2.4 m	Central MET Tower	Wind speed, m/s	Cup anemometer
308	NLMWS17M	N local met WS 17.02 m (hub height)	North MET Tower	Wind speed, m/s	Cup anemometer
310	NLMWD17M	N local met WD 17.02 m (hub height)	North MET Tower	Wind Direction, deg	Bi-vane anemometer
312	NLMWE17M	N local met WE 17.02 m (hub height)	North MET Tower	Wind Elevation, deg	Bi-vane anemometer
314	SLMWS17M	S local met WS 17.02 m (hub height)	South MET Tower	Wind speed, m/s	Cup anemometer
316	SLMWD17M	S local met WD 17.02 m (hub height)	South MET Tower	Wind Direction, deg	Bi-vane anemometer
318	SLMWE17M	S local met WE 17.02 m (hub height)	South MET Tower	Wind Elevation, deg	Bi-vane anemometer
320	LMT2M	Local met temperature 2.4m	Central MET Tower	Ambient air temperature, degC	Platinum resistance element (100 ohm)
322	LMDT	Local met Delta Temperature	Central MET Tower	Delta temperature, degC	Platinum resistance element (100 ohm)
324	LMDP2M	Local met dewpoint 2.4m	Central MET Tower	Dewpoint temperature, degC	Dewpoint temperature sensor
326	LMSU17M	Local met sonic channel U 17.02 m	Central MET Tower	Horizontal wind speed perpendicular to rotor plane, m/s	Sonic Anemometer
328	LMSV17M	Local met sonic channel V 17.02 m	Central MET Tower	Horizontal wind speed parallel to rotor plane, m/s	Sonic Anemometer
330	LMSW17M	Local met sonic channel W 17.02 m	Central MET Tower	Vertical wind speed, m/s	Sonic Anemometer

Table 25. Phase V Instrumentation Summary (continued)

Channel	ID Code	Description	Sensor Location	Measurement Type and Units	Sensor Type
332	GENPOW	Generator power	Nacelle bed plate	Generator power, kW	AC watt transducer
334	BARO	Barometric pressure	Data shed	Ambient air pressure, Pa	Ambient air pressure transducer
336	NAACYW	Nacelle Accelerometer Yaw	Nacelle bed plate	Linear yaw acceleration, m/s2	Accelerometer
338	NAACFA	Nacelle Accelerometer Fore-Aft	Nacelle bed plate	Linear fore-aft acceleration, m/s2	Accelerometer
340	NAACPI	Nacelle Accelerometer Pitch	Nacelle bed plate	Linear pitch acceleration, m/s2	Accelerometer
342	NAYM	Nacelle Yaw Moment	Arm of yaw brake	Bending moment, Nm	Strain gauge
349	B3AZI	Blade azimuth angle	Blade 3 hub/nacelle attachment	Angular position, deg	Digital position encoder
351	YAW	Yaw angle	Tower/nacelle attachment	Angular position, deg	Digital position encoder
353	DAY	Clock - day	Data shed	Time, day	Time code generator
355	HOUR	Clock - hour	Data shed	Time, hour	
357	MINUTE	Clock - minute	Data shed	Time, minute	
359	SECOND	Clock - second	Data shed	Time, second	
361	MILLISEC	Clock - millisecond	Data shed	Time, millisecond	

Table 25. Phase V Instrumentation Summary (continued)

Channel	ID Code	Power Requirement	Sensor Range	Nominal 12-bit DAS Resolution	Manufacturer-Stated Sensor Accuracy	Manufacturer and Model Number
000-050 (even)	Ptt30ccc Ptt36ccc Ptt41ccc	5Vdc, +/- 12Vdc	+/- 5 V = +/- 2500 Pa	1.2 Pa / bit	+/- 0.1 % full scale (static)	Pressure Systems, Inc. ESP-32
052-060 (even)	5Hx34	5Vdc, +/- 12Vdc	+/- 5 V = +/- 2500 Pa	1.2 Pa / bit	+/- 0.1 % full scale (static)	Pressure Systems, Inc. ESP-32
001-051 (odd)	Ptt47ccc Ptt52ccc Ptt58ccc	5Vdc, +/- 12Vdc	+/- 5 V = +/- 2500 Pa	1.2 Pa / bit	+/- 0.1 % full scale (static)	Pressure Systems, Inc. ESP-32
053-061 (odd)	5Hx51	5Vdc, +/- 12Vdc	+/- 5 V = +/- 2500 Pa	1.2 Pa / bit	+/- 0.1 % full scale (static)	Pressure Systems, Inc. ESP-32
100-150 (even)	Ptt63ccc Ptt69ccc Ptt74ccc	5Vdc, +/- 12Vdc	+/- 5 V = +/- 5000 Pa	2.4 Pa / bit	+/- 0.1 % full scale (static)	Pressure Systems, Inc. ESP-32
152-160 (even)	5Hx67	5Vdc, +/- 12Vdc	+/- 5 V = +/- 5000 Pa	2.4 Pa / bit	+/- 0.1 % full scale (static)	Pressure Systems, Inc. ESP-32
101-151 (odd)	Ptt80ccc Ptt85ccc Ptt90ccc	5Vdc, +/- 12Vdc	+/- 5 V = +/- 10342 Pa	5.0 Pa / bit	+/- 0.1 % full scale (static)	Pressure Systems, Inc. ESP-32
153-161 (odd)	5Hx84	5Vdc, +/- 12Vdc	+/- 5 V = +/- 10342 Pa	5.0 Pa / bit	+/- 0.1 % full scale (static)	Pressure Systems, Inc. ESP-32
200-250 (even)	Ptt95ccc Ptt92ccc Ptt98ccc	5Vdc, +/- 12Vdc	+/- 5 V = +/- 10342 Pa	5.0 Pa / bit	+/- 0.1 % full scale (static)	Pressure Systems, Inc. ESP-32
252-260 (even)	5Hx91	5Vdc, +/- 12Vdc	+/- 5 V = +/- 10342 Pa	5.0 Pa / bit	+/- 0.1 % full scale (static)	Pressure Systems, Inc. ESP-32
201	B1ACFL	15Vdc	+/- 2 V = +/- 10g	0.024 mps2 / bit	200 mV/g	Endevco Corporation 7290A-10
203	B1ACED	15Vdc	+/- 2 V = +/- 10g	0.024 mps2 / bit	200 mV/g	Endevco Corporation 7290A-10
209	B3ACFL	15Vdc	+/- 2 V = +/- 10g	0.024 mps2 / bit	200 mV/g	Endevco Corporation 7290A-10
211	B3ACED	15Vdc	+/- 2 V = +/- 10g	0.024 mps2 / bit	200 mV/g	Endevco Corporation 7290A-10
213	Not recorded		0 to 13.8 MPa	3.3 kPa / bit		IMO 303H2-12CG-10-P
215	HSXXB	+/- 10 Vdc	0-4096 counts=+/-14000 Nm	7 Nm/bit		Measurements Group, Inc. LWK-06-W250B-350
217	HSYYB	+/- 10 Vdc	0-4096 counts=+/-14000 Nm	7 Nm/bit		Measurements Group, Inc. LWK-06-W250B-350
219	HSTQ1	+/- 10 Vdc	0-4096 counts=+/-20000 Nm	10.5 Nm/bit		Measurements Group, Inc. LWK-06-W250D-350
221	HSTQ2	+/- 10 Vdc	0-4096 counts=+/-20000 Nm	10.5 Nm/bit		Measurements Group, Inc. LWK-06-W250D-350
223	TLINKF	10 Vdc	0-10 V = +/- 10,000 lbs	32 N/bit	0.1% full scale	Transducer Techniques HSW-10K

Table 25. Phase V Instrumentation Summary (continued)

Channel	ID Code	Power Requirement	Sensor Range	Nominal 12-bit DAS Resolution	Manufacturer-Stated Sensor Accuracy	Manufacturer and Model Number
225	B1RFB	+/- 10 Vdc	0-4096 counts=+/-16000 Nm	8 Nm / bit		Measurements Group, Inc. LWK-09-W250B-350
227	B1REB	+/- 10 Vdc	0-4096 counts=+/-16000 Nm	8 Nm / bit		Measurements Group, Inc. LWK-09-W250B-350
229	B1TDAMP	10 Vdc	0-10 V = 0-10,000 lbs	30 N/bit	0.25% full scale	Sensotec 5310239-08
231	B3TDAMP	10 Vdc	0-10 V = 0-10,000 lbs	30 N/bit	0.25% full scale	Sensotec 5310239-08
233	B3RFB	+/- 10 Vdc	0-4096 counts=+/-16000 Nm	8 Nm / bit		Measurements Group, Inc. LWK-09-W250B-350
235	B3REB	+/- 10 Vdc	0-4096 counts=+/-16000 Nm	8 Nm / bit		Measurements Group, Inc. LWK-09-W250B-350
237	LSSXXB	+/- 10 Vdc	0-4096 counts=+/-33000 Nm	16.5 Nm / bit		Measurements Group, Inc. CEA-06-250UW-350
239	LSSYYB	+/- 10 Vdc	0-4096 counts=+/-33000 Nm	16.5 Nm / bit		Measurements Group, Inc. CEA-06-250UW-350
241	LSSTQ	+/- 10 Vdc	0-4096 counts=+/-39000 Nm	19.5 Nm / bit		Measurements Group, Inc. CEA-06-250US-350
251	B1FLAP	15 Vdc	0-4096 counts = 0-45 deg	0.11 deg/bit	+/- 0.5 count (worst case)	BEI Motion Systems Company, RAS-25-4096
253	B1PITCH	+/- 15 Vdc, 5V	0-4096 counts = 0-360 deg	0.088 deg / bit	+/- 0.5 count (worst case)	BEI Motion Systems Company, R25-4096-24
255	B3FLAP	15 Vdc	0-4096 counts = 0-45 deg	0.11 deg/bit	+/- 0.5 count (worst case)	BEI Motion Systems Company, RAS-25-4096
257	B3PITCH	+/- 15 Vdc, 5V	0-4096 counts = 0-360 deg	0.088 deg / bit	+/- 0.5 count (worst case)	BEI Motion Systems Company, R25-4096-24
259, 261	VBL176 VBL178	12 Vdc	+/- 13,790 Pa	0.42 Pa / bit	0.025% full scale (standard)	Mensor Corporation 4010
300	LMWS24M	+/- 12 Vdc	0-5 V = 0-50 m/s	0.01 m/s / bit	+/- 1% of true	Met One Instruments 1564B, 170-41, 21.11
302	LMWS17M	+/- 12 Vdc	0-5 V = 0-50 m/s	0.01 m/s / bit	+/- 1% of true	Met One Instruments 1564B, 170-41, 21.11
304	LMWS10M	+/- 12 Vdc	0-5 V = 0-50 m/s	0.01 m/s / bit	+/- 1% of true	Met One Instruments 1564B, 170-41, 21.11
306	LMWS2M	+/- 12 Vdc	0-5 V = 0-50 m/s	0.01 m/s / bit	+/- 1% of true	Met One Instruments 1564B, 170-41, 21.11
308	NLMWS17M	+/- 12 Vdc	0-5 V = 0-50 m/s	0.01 m/s / bit	+/- 1% of true	Met One Instruments 1564B, 170-41, 21.11
310	NLMWD17M	+/- 12 Vdc	0-5 V = 0-360 deg	0.088 deg / bit	+/- 2 deg	Met One Instruments 1585, 21.21
312	NLMWE17M	+/- 12 Vdc	0-5 V = -60 to 60 deg	0.03 deg / bit	+/- 2 deg	Met One Instruments 1585, 21.21
314	SLMWS17M	+/- 12 Vdc	0-5 V = 0-50 m/s	0.01 m/s / bit	+/- 1% of true	Met One Instruments 1564B, 170-41, 21.11
316	SLMWD17M	+/- 12 Vdc	0-5 V = 0-360 deg	0.088 deg / bit	+/- 2 deg	Met One Instruments 1585, 21.21
318	SLMWE17M	+/- 12 Vdc	0-5 V = -60 to 60 deg	0.03 deg / bit	+/- 2 deg	Met One Instruments 1585, 21.21
320	LMT2M	+/- 12 Vdc	0-5 V = -50 to 50 degC	0.02 deg / bit	+/- 0.1 degC to+/- 0.3 degC	Met One Instruments T200, 21.32A4
322	LMDT	+/- 12 Vdc	0-5 V = -8 to 12 degF	0.005 degC / bit	+/- 0.2 degC to +/- 0.6 degC	Met One Instruments T200, Teledyne ModS22 rev. E
324	LMDP2M	+/- 12 Vdc	0-5 V = -50 to 50 degC	0.02 deg / bit	+/- 0.1 degC to+/- 0.3 degC	Met One Instruments DP200B, 21.43D2
326	LMSU17M	120 Vac	+/- 5 V = +/- 50 m/s	0.02 m/s / bit	+/- 1 % or +/- 0.05 m/s	Applied Technologies, Inc. SWS-211/3K
328	LMSV17M	120 Vac	+/- 5 V = +/- 50 m/s	0.02 m/s / bit	+/- 1 % or +/- 0.05 m/s	Applied Technologies, Inc. SWS-211/3K
330	LMSW17M	120 Vac	+/- 5 V = +/- 15 m/s	0.01 m/s / bit	+/- 1 % or +/- 0.05 m/s	Applied Technologies, Inc. SWS-211/3K

Table 25. Phase V Instrumentation Summary (continued)

Channel	ID Code	Power Requirement	Sensor Range	Nominal 12-bit DAS Resolution	Manufacturer-Stated Sensor Accuracy	Manufacturer and Model Number
332	GENPOW	240 Vac	+/- 5V = +/- 40 kW	0.02 kW / bit	+/- 0.5% at rated power	Ohio Semitronics, Inc. PC5-63C
334	BARO	15Vdc	0-5 V = 74000 - 100000 Pa	6.3 Pa / bit		Atmospheric Instrumentation Research, Inc. AIR-AB-2AX
336	NAACYW	15Vdc	+/- 2 V = +/- 10g	0.024 mps2 / bit	200 mV/g	Endevco Corporation 7290A-10
338	NAACFA	15Vdc	+/- 2 V = +/- 10g	0.024 mps2 / bit	200 mV/g	Endevco Corporation 7290A-10
340	NAACPI	15Vdc	+/- 2 V = +/- 10g	0.024 mps2 / bit	200 mV/g	Endevco Corporation 7290A-10
342	NAYM	+/- 10 Vdc	0-4096 counts=+/- 5500 Nm	2.7 Nm / bit		Measurements Group, Inc.
349	B3AZI	15Vdc	0-4096 counts = 0-360 deg	0.088 deg / bit	+/- 0.5 count (worst case)	BEI Motion Systems Company, R25-4096-24
351	YAW	15Vdc	0-4096 counts = 0-360 deg	0.088 deg / bit	+/- 0.5 count (worst case)	BEI Motion Systems Company, R25-4096-25
353	DAY	120 Vac	0-4096 counts=binary coded decimal digital	0.1 ms	Frequency stability +/- 5ppm	9310-804
355	HOUR					
357	MINUTE					
359	SECOND					
361	MILLISEC					

Table 25. Phase V Instrumentation Summary (continued)

Channel	ID Code	Signal Conditioning	Analog Anti-Alias Filters	Calibration Methods	Page Number
000-050 (even)	Ptt30ccc Ptt36ccc Ptt41ccc	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-46
052-060 (even)	5Hx34	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-46
001-051 (odd)	Ptt47ccc Ptt52ccc Ptt58ccc	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-46
053-061 (odd)	5Hx51	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-46
100-150 (even)	Ptt63ccc Ptt69ccc Ptt74ccc	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-48
152-160 (even)	5Hx67	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-48
101-151 (odd)	Ptt80ccc Ptt85ccc Ptt90ccc	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-49
153-161 (odd)	5Hx84	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-49
200-250 (even)	Ptt95ccc Ptt92ccc Ptt98ccc	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-49
252-260 (even)	5Hx91	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-49
201	B1ACFL	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-35
203	B1ACED	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-35
209	B3ACFL	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-35
211	B3ACED	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-35
213	Not recorded	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter		B-51
215	HSXXB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-25
217	HSYYB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-25
219	HSTQ1	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-25
221	HSTQ2	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-25
223	TLINKF	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A3	B-21

Table 25. Phase V Instrumentation Summary (continued)

Channel	ID Code	Signal Conditioning	Analog Anti-Alias Filters	Calibration Methods	Page Number
225	B1RFB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-29
227	B1REB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-29
229	B1TDAMP	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A4, S5	B-23
231	B3TDAMP	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A4, S5	B-23
233	B3RFB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-29
235	B3REB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-29
237	LSSXXB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-31
239	LSSYYB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-31
241	LSSTQ	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-31
251	B1FLAP			M13, S6	B-43
253	B1PITCH			M9, S3	B-40
255	B3FLAP			M13, S6	B-43
257	B3PITCH			M9, S3	B-40
259, 261	VBL176 VBL178			M11	B-52
300	LMWS24M	Wind speed processor (Met One Instruments, 21.11)	Butterworth Filter	M1, E1	B-2
302	LMWS17M	Wind speed processor (Met One Instruments, 21.11)	Butterworth Filter	M1, E1	B-2
304	LMWS10M	Wind speed processor (Met One Instruments, 21.11)	Butterworth Filter	M1, E1	B-2
306	LMWS2M	Wind speed processor (Met One Instruments, 21.11)	Butterworth Filter	M1, E1	B-2
308	NLMWS17M	Wind speed processor (Met One Instruments, 21.11)	Butterworth Filter	M1, E1	B-2
310	NLMWD17M	Wind direction processor (Met One Inst., 21.21)	Butterworth Filter	M2, S1, E1	B-5
312	NLMWE17M	Wind direction processor (Met One Inst., 21.21)	Butterworth Filter	M3, S2, E1	B-5
314	SLMWS17M	Wind speed processor (Met One Instruments, 21.11)	Butterworth Filter	M1, E1	B-2
316	SLMWD17M	Wind direction processor (Met One Inst., 21.21)	Butterworth Filter	M2, S1, E1	B-5
318	SLMWE17M	Wind direction processor (Met One Inst., 21.21)	Butterworth Filter	M3, S2, E1	B-5
320	LMT2M	Temperature processor (Met One Instruments, 21.32A4)	Butterworth Filter	M5, E1	B-14
322	LMDT	Delta temperature processor (Teledyne ModS22 rev. E and Met One Inst., 21.32)	Butterworth Filter	M5, E1	B-14
324	LMDP2M	Dewpoint temperature processor (Met One Inst., 21.43D2)	Butterworth Filter	M5, E1	B-15
326	LMSU17M	RS232C to +/- 5 Vdc (Applied Technologies, Inc., SA-4)	Butterworth Filter	M4, E1	B-11
328	LMSV17M	RS232C to +/- 5 Vdc (Applied Technologies, Inc., SA-4)	Butterworth Filter	M4, E1	B-11
330	LMSW17M	RS232C to +/- 5 Vdc (Applied Technologies, Inc., SA-4)	Butterworth Filter	M4, E1	B-11

Table 25. Phase V Instrumentation Summary (continued)

Channel	ID Code	Signal Conditioning	Analog Anti-Alias Filters	Calibration Methods	Page Number
332	GENPOW	+/- 5 Vdc to +/- 5 Vdc (Analog Devices, Inc. 5B41-02)	Butterworth Filter	M7, E1	B-38
334	BARO	+/- 5 Vdc to +/- 5 Vdc (Analog Devices, Inc. 5B41-02)	Butterworth Filter	M6, E1	B-19
336	NAACYW	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-35
338	NAACFA	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-35
340	NAACPI	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-35
342	NAYM	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Butterworth Filter	A1	B-34
349	B3AZI			M9, S3	B-40
351	YAW			M9, S3	B-40
353	DAY			M12	B-54
355	HOUR				
357	MINUTE				
359	SECOND				
361	MILLISEC				

Appendix D

Data Index

Table 26. Phase V Data Index

Campaign	Mean Blade 3 Pitch (deg)	Mean H.H. Wind Speed (m/s)	Mean Sonic Wind Speed (m/s)	Mean North Wind Direction (deg)	Mean South Wind Direction (deg)	Mean Sonic Wind Direction (deg)	Mean Richardson Number	Mean Yaw Error Angle (deg)	Blade 1 Max. Teeter Damper Force (N)	Blade 3 Max. Teeter Damper Force (N)	Comments	Problems	Calibration History
d503003	2.981	8.710	8.588	288.815	289.214	288.559	-0.038	-5.622	-135.216	229.844	2	A	I,II
d503004	2.990	9.774	9.470	294.941	294.595	294.592	-0.105	-4.765	-136.440	218.164	2,6	A	III
d503005	2.968	8.911	8.662	301.331	301.872	301.558	-0.054	-2.734	-141.410	210.080	2	A,B	III
d503006	2.939	7.520	7.279	289.100	288.737	288.183	-0.019	-1.620	-136.150	220.797	2	A,B	III
d503007	2.938	7.614	7.474	279.590	279.485	278.808	-0.046	-4.454	-133.691	221.166	2	A,B	III
d503008	2.994	8.900	8.649	297.217	297.235	297.222	0.020	-1.172	-125.992	246.943	2,6	A	III
d503009	2.990	8.485	8.249	282.456	282.562	281.809	0.036	-4.346	-120.282	260.656	2	A	III
d503010	2.970	8.652	8.541	268.562	268.983	267.511	0.031	-3.363	-111.972	274.470	2,6,7	A	III
d503011	2.989	11.194	11.089	271.291	271.600	270.526	0.021	-1.701	-107.773	279.094	2	A	III
d503012	2.989	10.129	9.999	268.977	269.077	267.825	0.021	-0.620	-101.611	289.912	2	A	III
d503013	2.989	10.876	10.765	268.390	268.915	267.524	0.022	-2.279	-100.647	297.176	2	A	III
d503014	2.989	10.188	10.081	266.673	266.842	265.468	0.024	-1.977	-98.061	300.670	2	A	III
d5m3001	-2.990	9.440	9.322	270.667	271.088	270.052	0.026	-2.966	-95.528	303.064	1,7	A	III
d5m3002	-2.996	6.882	6.637	286.037	286.698	285.359	0.050	-2.704	-96.571	301.070	1,8	A	III
d5m3003	-3.007	5.508	5.285	301.741	301.670	301.174	0.058	2.715	-95.417	303.157	1,8	A	III
d5m3004	-2.990	5.805	5.884	213.140	212.767	211.856	0.098	15.480	-97.361	300.290	1	A	III
d503017	2.988	7.084	6.846	280.508	281.334	279.749	-0.019	3.888	-88.431	335.929	2,8	A,C	II,IV,V
d503018	2.974	6.235	5.975	287.377	287.638	286.775	-0.011	-3.336	-85.492	334.983	2,6	A	III
d5m9001	-8.970	7.425	7.197	314.683	314.712	314.503	-0.136	-6.811	-99.809	294.716	4	A	III
d5m9002	-8.971	6.265	5.999	290.000	290.471	289.389	-0.208	0.293	-102.659	281.952	4	A	III
d503019	2.987	4.668	4.424	272.597	278.222	275.391	-0.471	20.514	-110.163	271.450	2	A	III
d503020	2.988	6.229	5.798	290.908	289.446	289.731	-0.348	1.330	-115.622	262.140	2	A	III
d5m3008	-2.991	11.013	10.789	280.094	280.622	279.681	-0.121	-3.778	-120.352	252.115	1,7	A	II
d503021	2.989	8.972	8.748	278.193	278.392	276.937	-0.171	-1.667	-118.904	251.969	2,7	A	III
d503022	2.988	10.301	10.143	276.010	276.532	275.103	-0.178	-4.708	-117.600	251.169	2,7	A	III
d503023	2.988	9.939	9.808	271.648	272.092	270.707	-0.143	-3.409	-116.351	251.130	2,7	A	III
d503024	2.988	10.354	10.223	271.338	271.829	270.378	-0.148	-2.054	-116.609	249.220	2,7	A	III
d508007	7.997	11.277	11.122	281.431	281.696	280.638	-0.098	-5.412	-117.086	249.470	2,7	A	III
d508008	7.997	9.666	9.423	276.282	275.932	275.279	-0.118	-6.159	-115.134	252.210	2,7	A	III
d5m3009	-2.991	8.984	8.794	274.010	274.443	273.217	-0.161	-0.879	-114.161	249.038	1,7	A	III
d5m3010	-2.991	10.590	10.410	263.098	263.369	261.703	-0.073	-0.535	-114.671	251.687	1,7	A	III
d5m3011	-2.991	8.884	8.702	274.537	274.706	273.761	-0.082	-0.580	-109.584	257.484	1,7	A	III

Table 26. Phase V Data Index (continued)

Campaign	Mean Blade 3 Pitch (deg)	Mean H.H. Wind Speed (m/s)	Mean Sonic Wind Speed (m/s)	Mean North Wind Direction (deg)	Mean South Wind Direction (deg)	Mean Sonic Wind Direction (deg)	Mean Richardson Number	Mean Yaw Error Angle (deg)	Blade 1 Max. Teeter Damper Force (N)	Blade 3 Max. Teeter Damper Force (N)	Comments	Problems	Calibration History
d5m3012	-2.990	5.697	5.412	279.884	280.649	279.255	-0.231	-1.406	-109.313	255.183	1,7	A	III
d503025	2.987	9.178	8.903	294.935	295.248	294.696	-0.148	-3.423	-112.238	242.138	2,7	A	III
d503026	2.988	9.417	9.217	306.118	305.842	306.035	-0.171	-3.873	-113.694	238.363	2,7	A	III
d503027	2.987	7.937	7.692	273.235	273.210	272.281	-0.225	-2.444	-111.332	235.840	2,7	A	III
d503028	2.989	16.563	16.271	251.460	251.756	249.684	-0.049	1.530	-113.948	233.736	2,7	A	III
d503029	2.988	11.018	10.874	236.607	236.291	233.901	-0.144	2.671	-119.131	242.174	2,7	A	III
d503030	2.988	10.926	10.707	251.225	251.658	249.579	-0.096	-2.474	-114.123	239.210	2,7	A	II
d508009	7.997	9.453	9.265	255.188	255.620	253.699	-0.126	-0.345	-118.090	230.318	3,7	A	III
d508010	7.997	11.515	11.281	253.749	254.073	252.251	-0.094	1.202	-120.333	225.928	3,7	A	III
d508011	7.996	10.339	10.165	259.081	259.295	257.833	-0.085	1.103	-114.942	232.180	3,7	A	III
d508012	7.996	7.990	7.858	252.039	252.106	250.029	-0.209	7.448	-116.080	229.714	3,7	A	III
d5m9003	-8.972	5.387	5.224	261.313	262.586	260.077	-0.244	1.965	-120.486	227.879	4,7	A	III
d5m9004	-8.971	6.712	6.532	251.407	251.826	249.211	0.011	3.930	-115.370	237.860	4,7	A	III
d5m9005	-8.973	12.196	12.046	264.938	265.374	263.993	0.003	5.140	-107.782	247.534	4,7	A	III
d512001	11.977	11.112	10.932	255.516	255.833	254.001	0.013	1.629	-105.490	247.983	5,7	A	III
d5y3001	2.989	9.558	9.466	271.329	271.215	270.204	-0.026	-5.959	-105.822	249.180	2,7,9	A	III
d5y3002	2.987	10.715	10.551	250.744	250.979	248.993	0.024	29.845	-103.068	254.737	2,7,9	A	III
d503031	2.988	10.839	10.723	254.011	254.374	252.371	0.025	2.208	-101.380	260.929	2,7	A	III
d503032	2.988	8.789	8.695	247.098	247.334	244.847	0.075	5.326	-101.255	261.418	2,7	A	III
d503033	2.988	8.128	8.101	264.474	265.279	263.366	0.086	1.841	-95.882	280.868	2	A	III
d5m9006	-8.970	6.151	6.045	268.418	268.853	267.095	0.202	-1.985	-91.374	282.011	4	A	III
d503034	2.988	9.749	9.527	265.694	264.150	264.174	0.013	0.274	109.747	163.838	2		I,II
d503035	2.988	9.749	9.556	270.811	268.885	269.144	0.011	2.011	109.688	165.583	2		III
d503036	2.987	9.649	9.476	251.529	249.816	249.317	0.011	-0.122	110.417	162.705	2		II
d503037	2.987	10.824	10.576	258.227	257.049	256.505	0.011	-0.232	108.849	160.847	2		II
d503038	2.987	7.605	7.380	261.976	260.270	260.152	0.015	0.296	112.334	162.266	2,10		III
d5pb012	79.975	23.935	25.513	271.152	269.694	261.507	0.033	9.950	20.954	5078.881	7,9	D,E	II
d5pb013	79.936	26.341	29.645	272.510	270.978	252.637	0.025	-9.181	60.284	5527.058	7	D,E	III, VI
d5pb014	60.107	24.786	27.134	271.073	269.822	256.584	0.027	3.880	69.921	3138.336	7,9	D,E	III, VI
d5pb015	90.003	20.349	25.648	278.896	277.807	248.308	0.028	-21.526	73.616	3640.677	7,11	D,E	III, VI
d5pb016	44.899	22.863	24.015	272.603	271.130	264.708	0.026	-3.128	75.542	1389.778	7,11		III, VI
d503039	2.990	6.444	6.436	269.445	267.446	269.658	-0.021	29.757	36.486	-29.134	2,9	F	II

Table 26. Phase V Data Index (concluded)

Campaign	Mean Blade 3 Pitch (deg)	Mean H.H. Wind Speed (m/s)	Mean Sonic Wind Speed (m/s)	Mean North Wind Direction (deg)	Mean South Wind Direction (deg)	Mean Sonic Wind Direction (deg)	Mean Richardson Number	Mean Yaw Error Angle (deg)	Blade 1 Max. Teeter Damper Force (N)	Blade 3 Max. Teeter Damper Force (N)	Comments	Problems	Calibration History
d503040	2.989	6.387	6.419	273.437	272.014	274.177	-0.046	-1.648	56.931	-16.466	2		III
d5m3013	-2.995	7.129	7.182	272.251	270.478	272.874	-0.003	-4.878	62.005	-5.890	1		III
d5m3014	-2.991	5.329	5.291	274.135	272.620	275.113	0.033	-2.846	66.728	-0.178	1		III
d5pb017	90.064	21.970	24.263	275.585	274.121	264.394	0.003	2.803	46.793	3936.622	7,9		II
d5pb018	90.055	21.290	22.568	276.711	275.623	271.149	0.002	6.509	79.914	3743.562			III
d5pb019	90.046	20.871	21.102	273.161	271.497	272.313	0.000	10.031	107.947	3610.395			III
d5pb020	79.992	19.676	21.024	278.376	277.298	273.543	-0.003	-6.812	129.270	3223.492	9		III
d5pb021	80.001	19.312	20.438	280.924	278.818	276.096	-0.006	-0.696	140.547	2968.051	7		III
d5pb022	75.060	20.284	21.587	278.243	276.771	272.548	-0.007	-4.721	148.815	2999.910	7	G	III

Suite of problems:

A. Low-speed shaft Y-Y bending not in operation
B. Pitch system failure (stuck at 3 degrees)
C. Cup Anemometer 17 m on north tower replaced.
D. Blowing snow caused sonic glitches
E. P2330.5L may have been blocked
F. 95% span transducer may not have gone into cal.
G. North anemometer possibly broken

Calibration history:

I. Full system calibration (all non-pressure channels)
II. Pressure channel pre-calibration performed
III. Pre-cal. obtained from post-cal. of previous campaign
IV. Meteorological channels signal conditioners calibration verified
V. Teeter damper contact angle re-confirmed.
VI. Transducer at 47% span reading 1 count when should be zero. This was fixed prior to post-processing

Night Video
Collected during fall 1998

Suite of comments:

1. -3° pitch
2. 3° pitch
3. 8° pitch
4. -9° pitch
5. 12° pitch
6. Pitch angle switched from manual to automatic during run
7. No video
8. Manual pitch mode throughout
9. Yaw locked
10. Turned upwind during run
11. Yaw brake slipped

Appendix E

Additional Figures

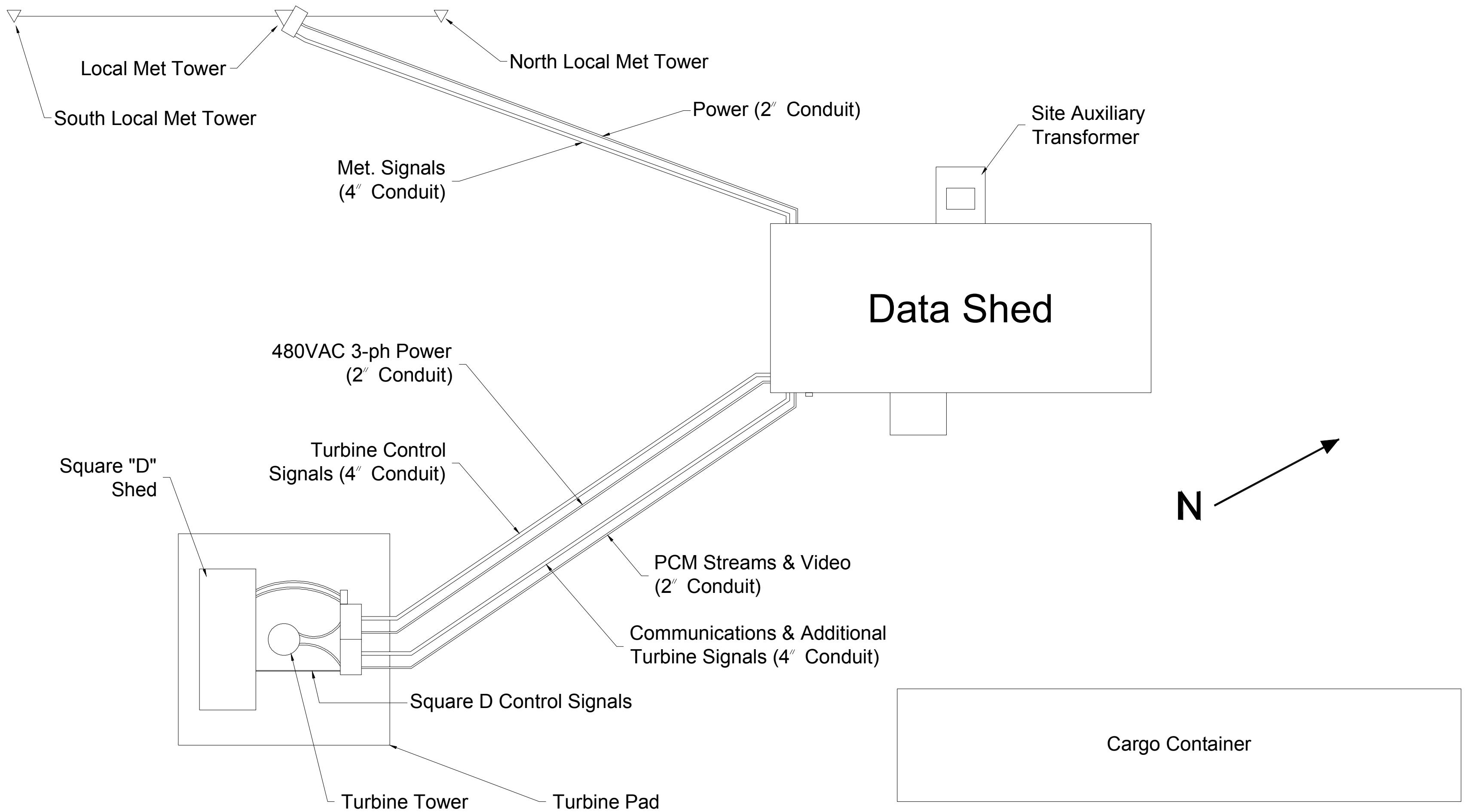


Figure 54. Aerial view of site layout

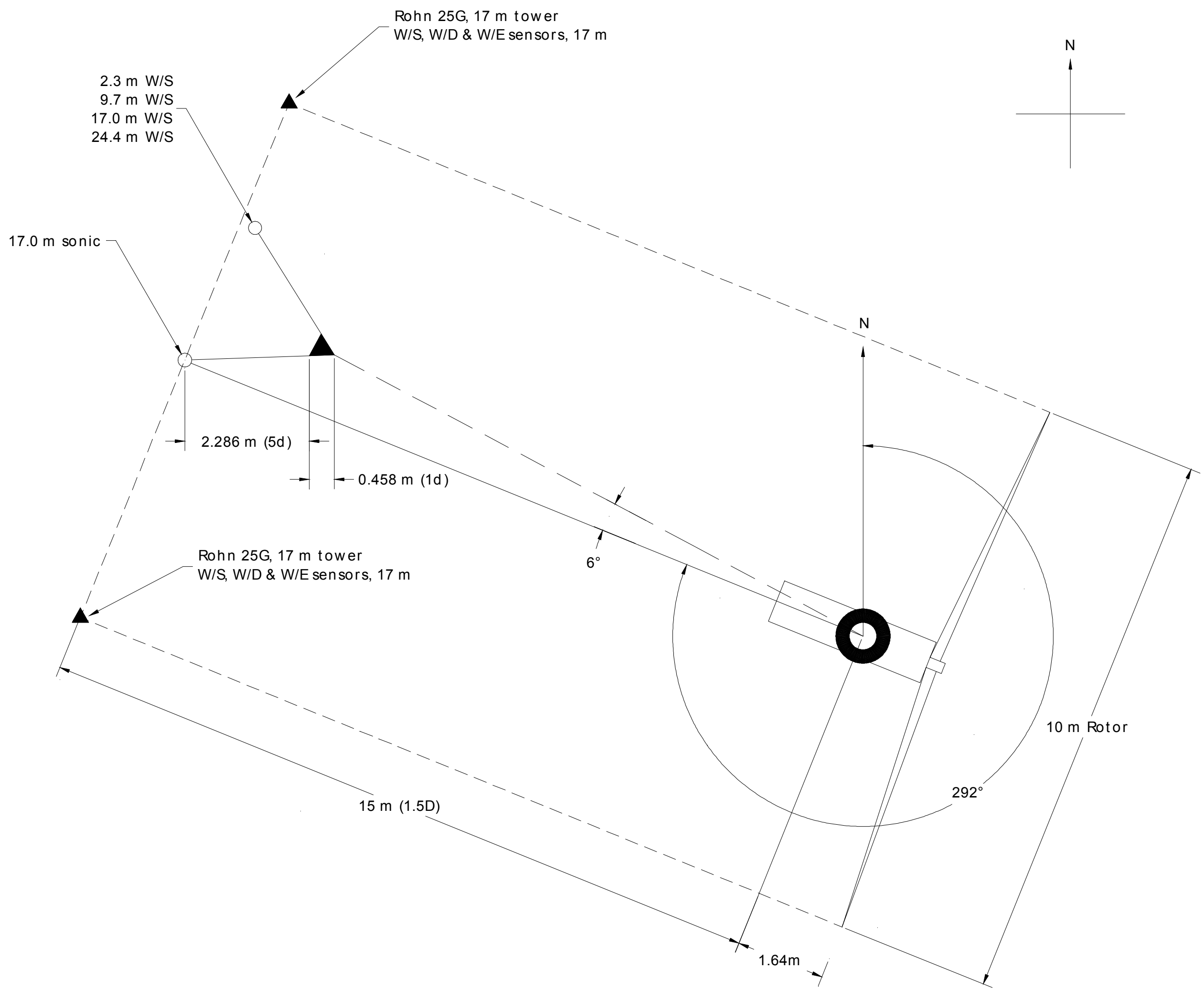


Figure 55. Plan view of site showing location of meteorological instruments relative to turbine

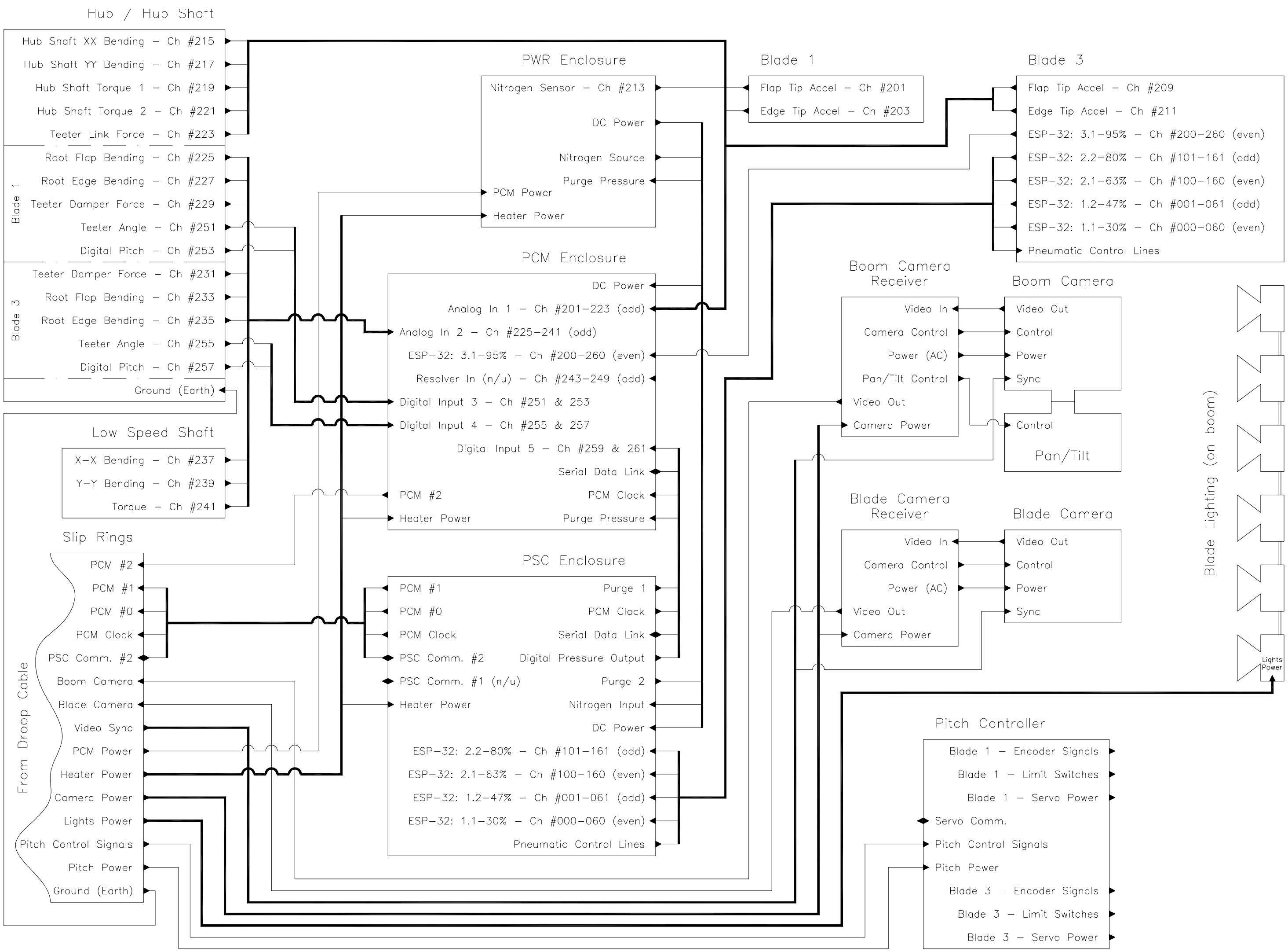


Figure 56. Rotor instrumentation block diagram

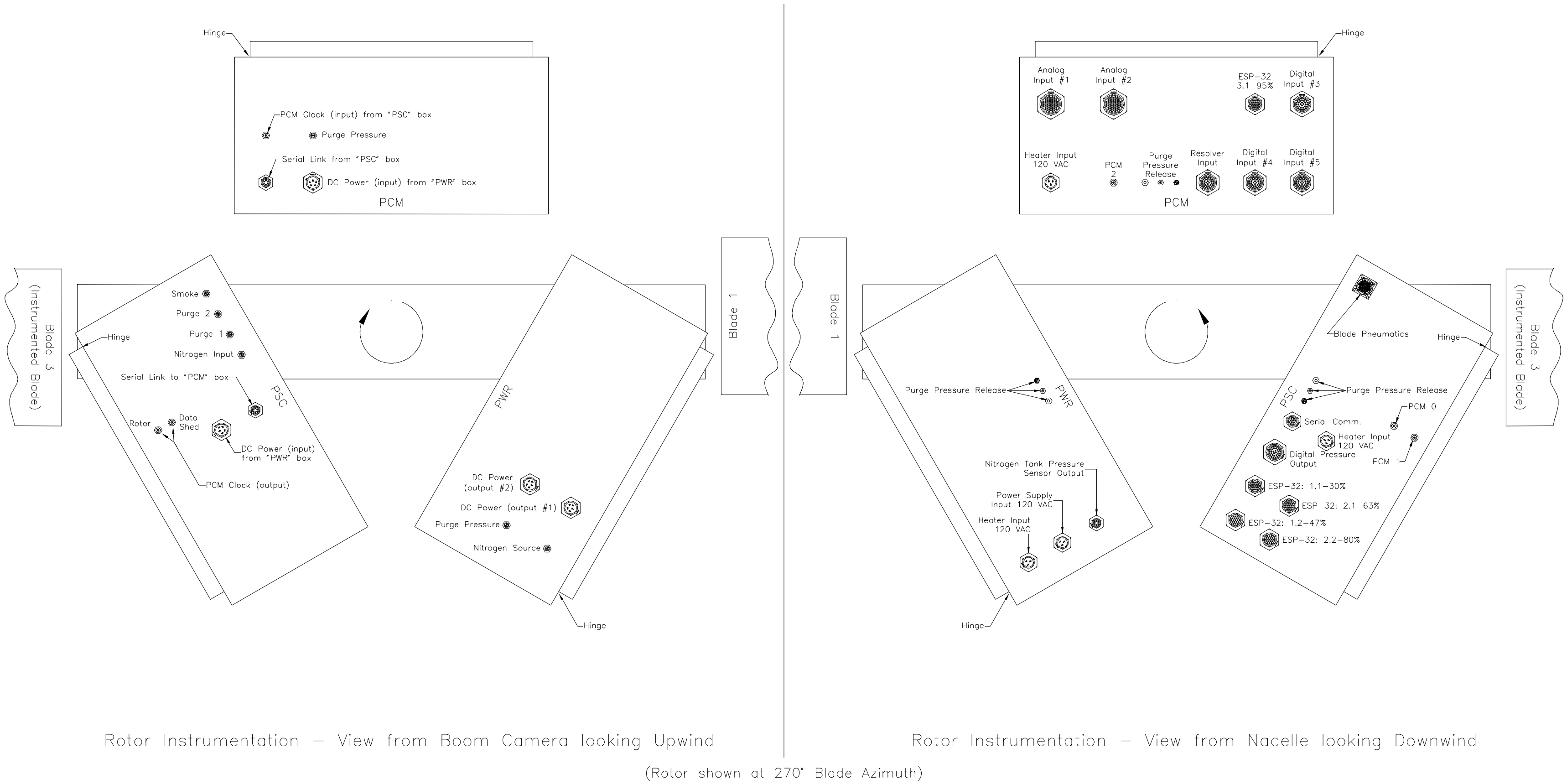


Figure 57. Rotor instrumentation enclosure and connector layout

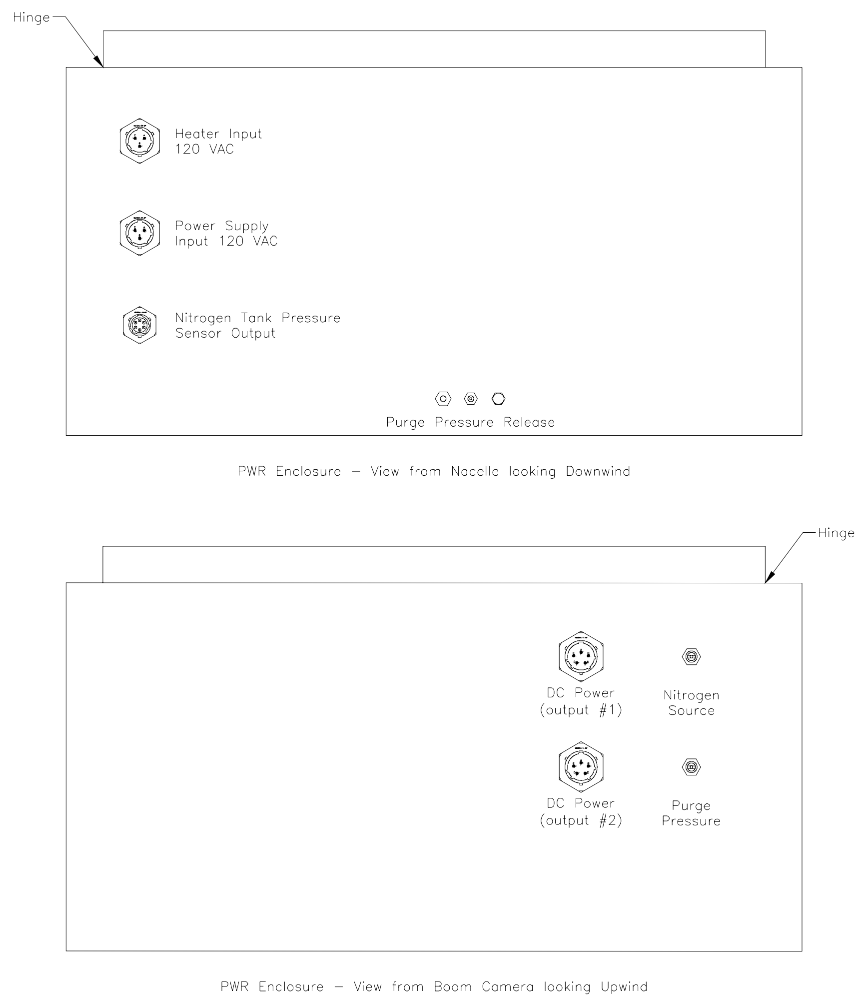
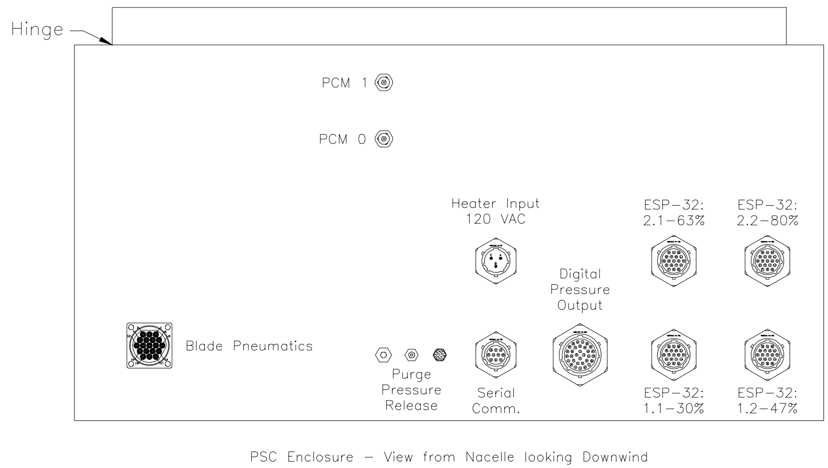


Figure 58. Rotor-based PWR enclosure (side view)



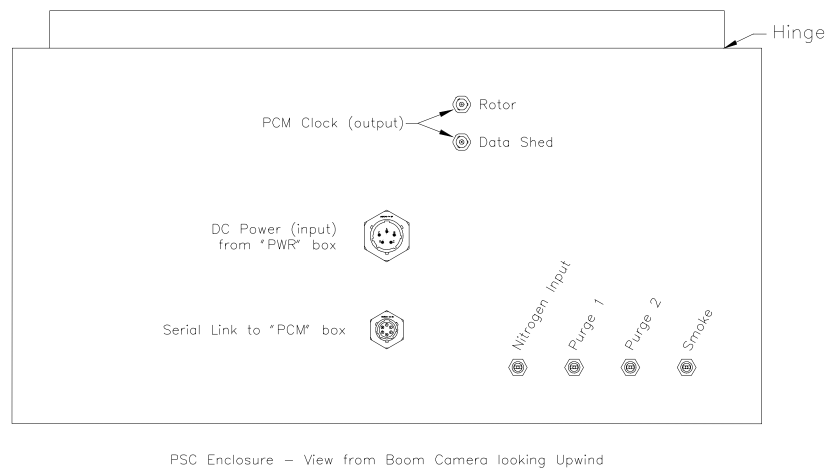


Figure 59. Rotor-based PSC enclosure (side view)

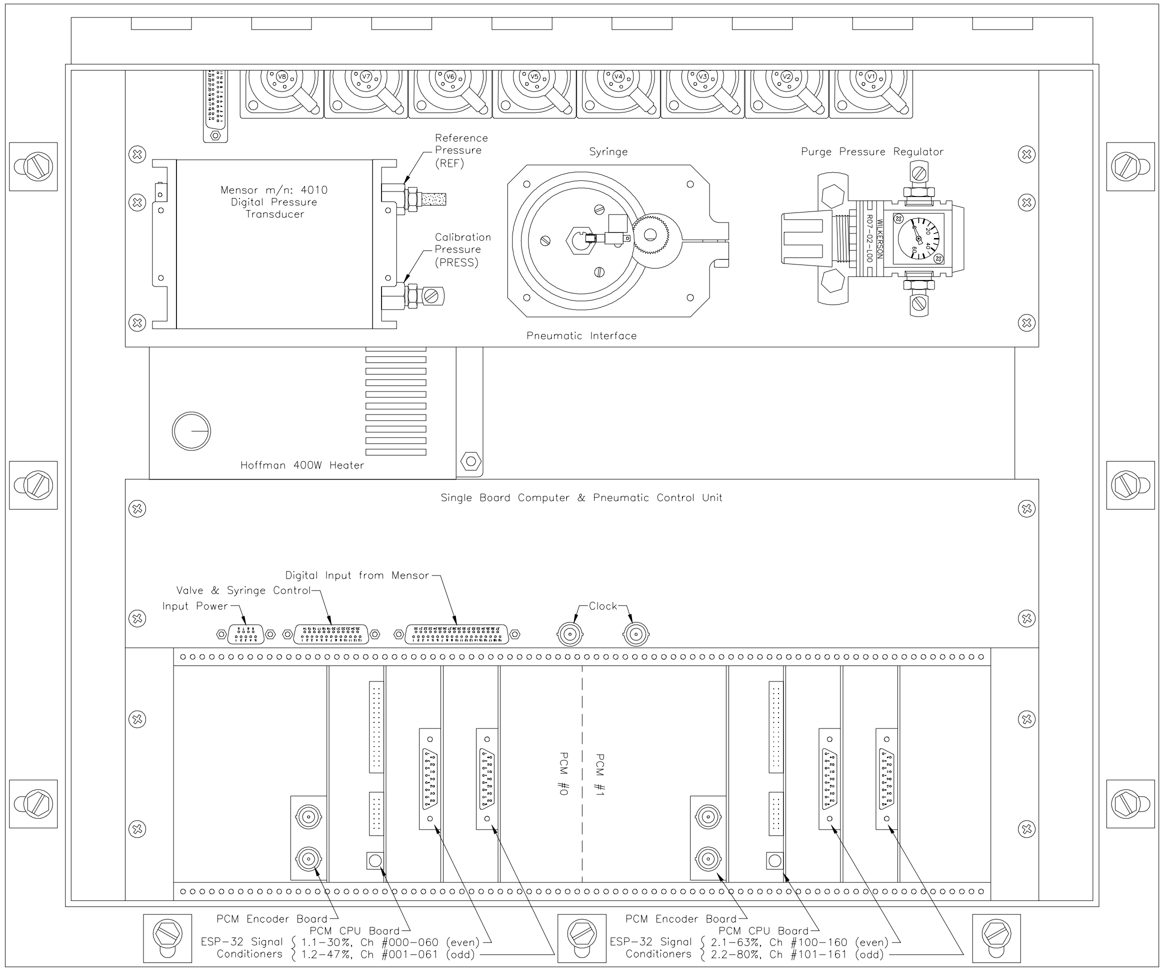


Figure 60. Rotor-based PSC enclosure (top view)

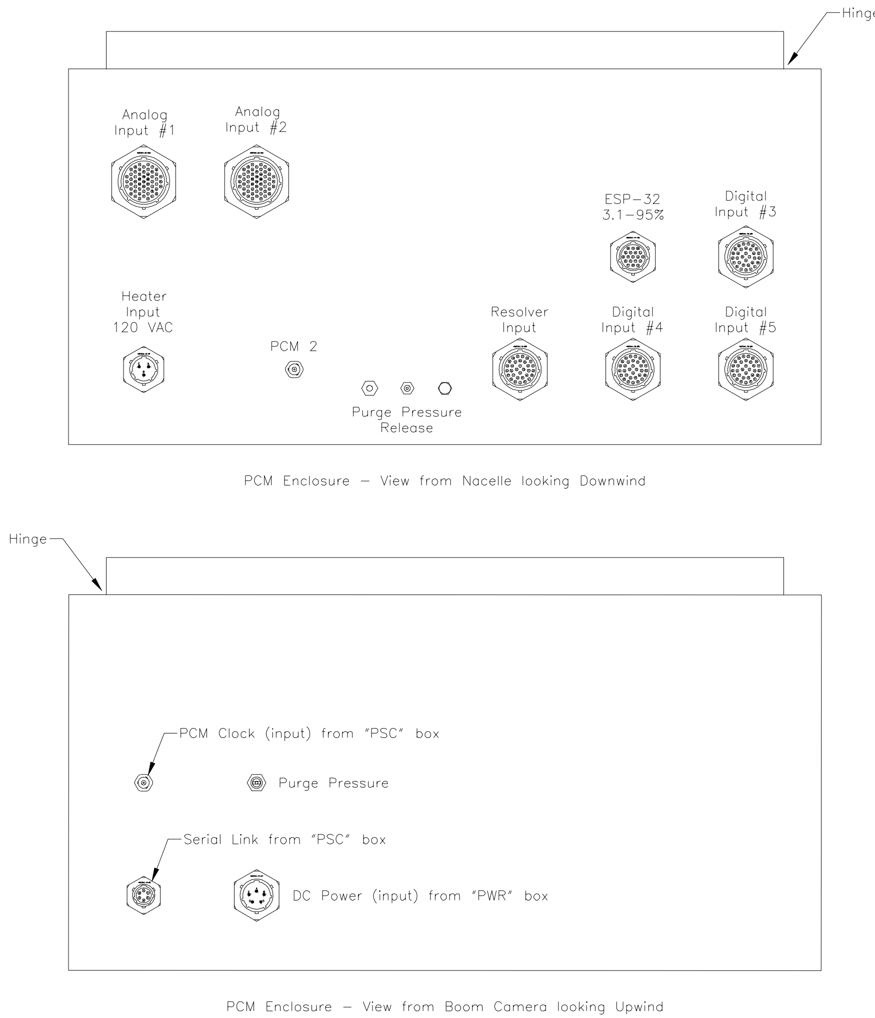


Figure 61. Rotor-based PCM enclosure (side view)

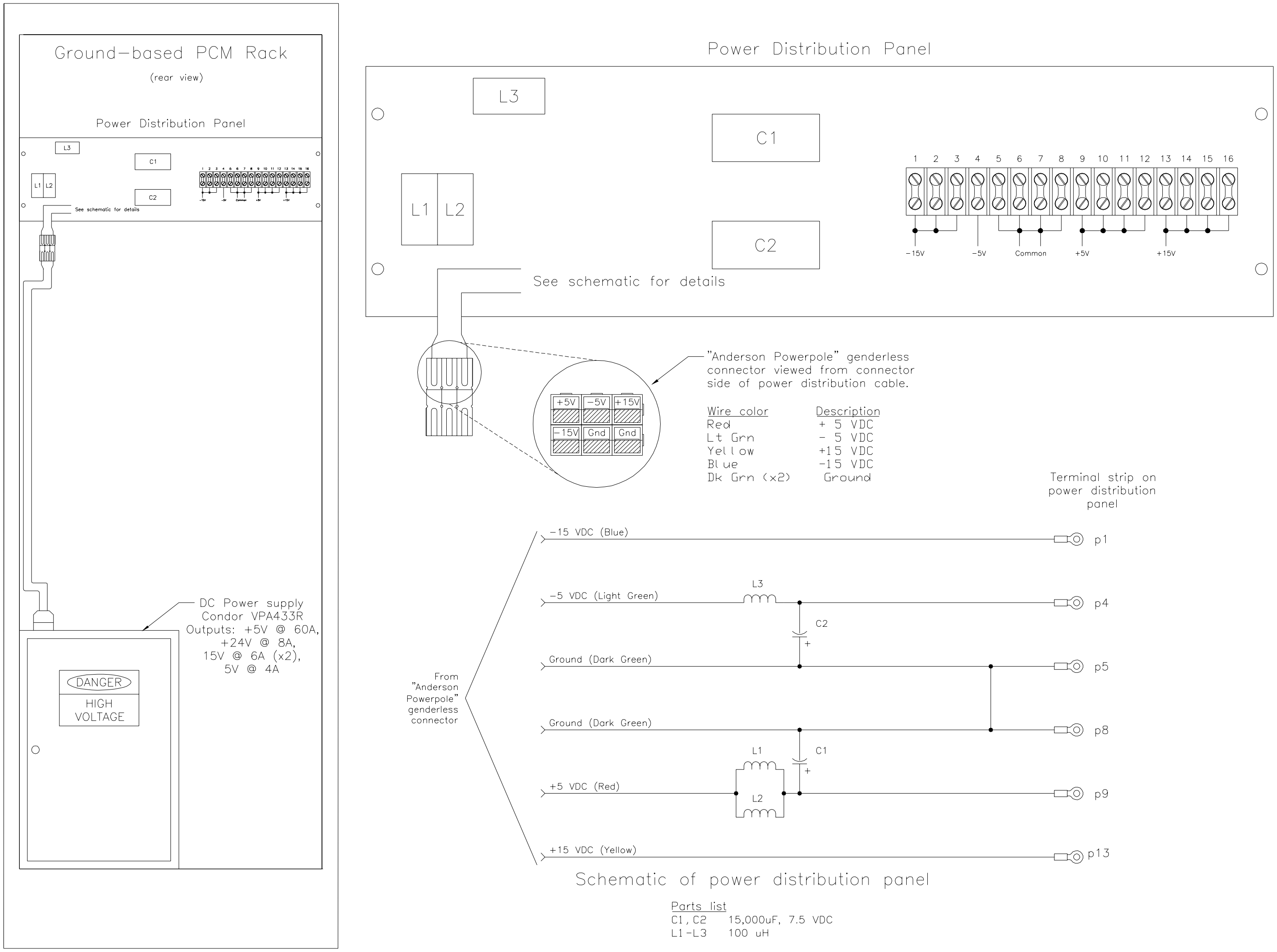


Figure 62. Ground-based PCM rack power

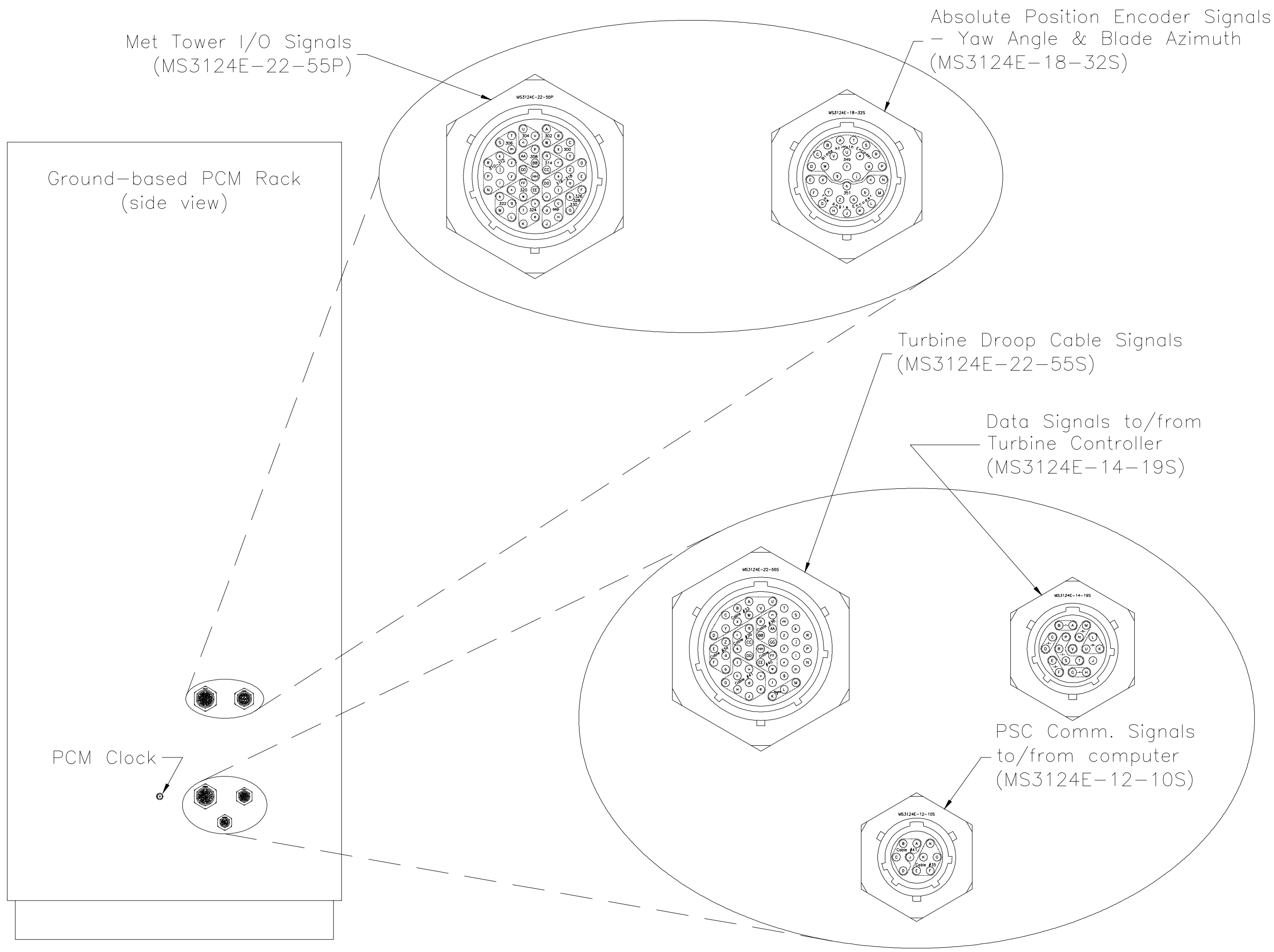


Figure 63. Ground-based PCM rack I/O

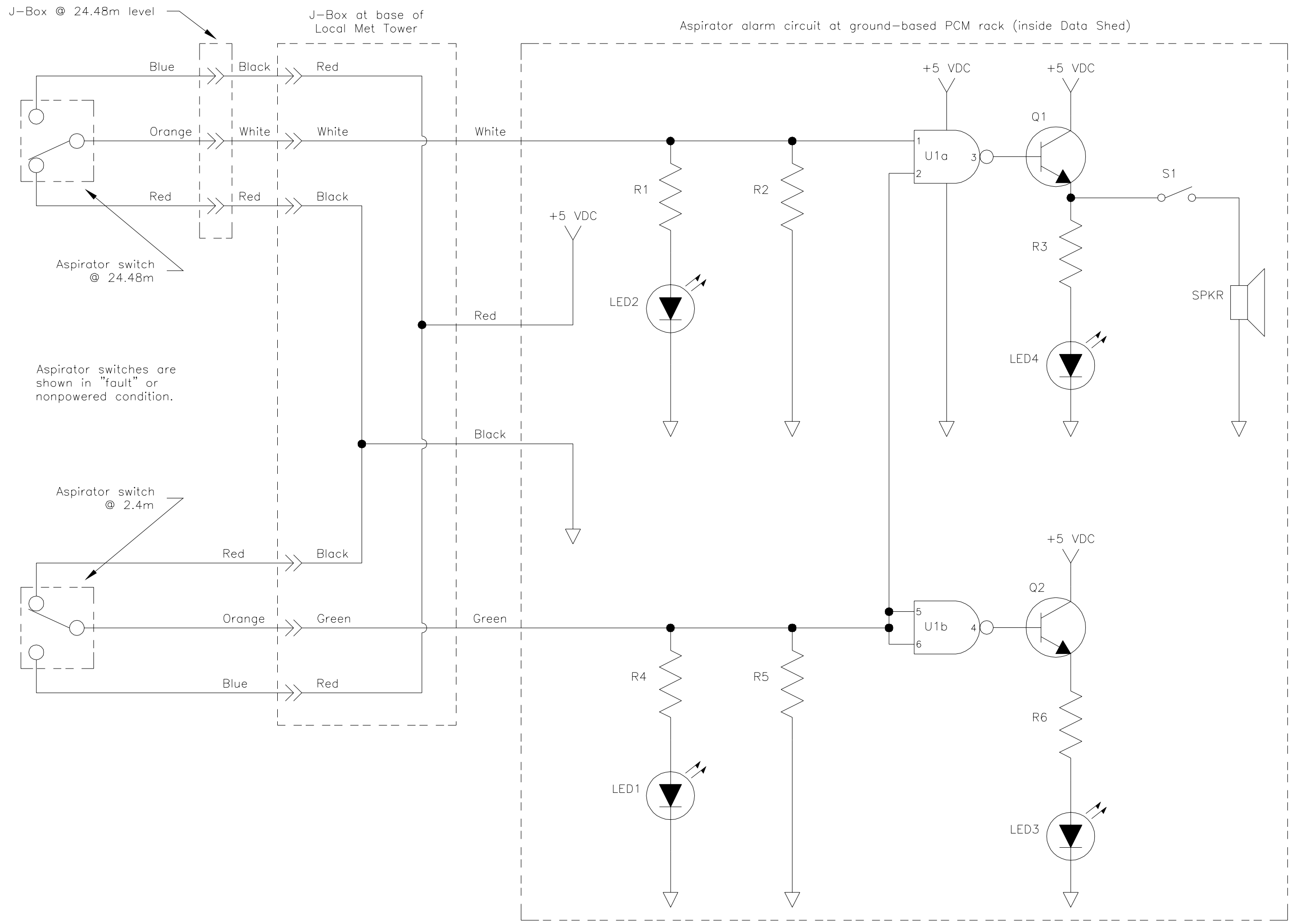
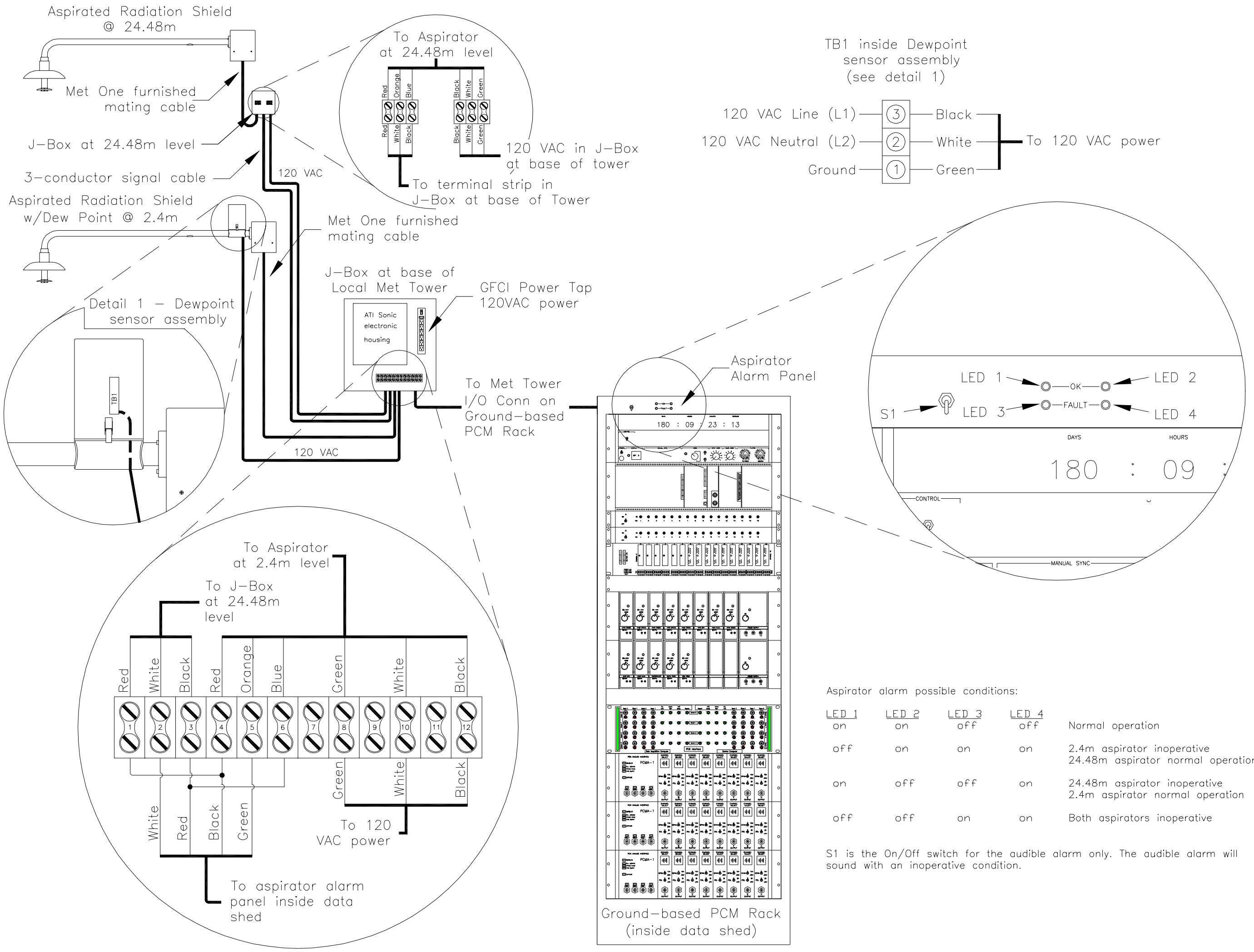


Figure 64. Aspirator alarm panel schematic



Aspirator alarm possible conditions:

LED 1	LED 2	LED 3	LED 4	
on	on	off	off	Normal operation
off	on	on	on	2.4m aspirator inoperative 24.48m aspirator normal operation
on	off	off	on	24.48m aspirator inoperative 2.4m aspirator normal operation
off	off	on	on	Both aspirators inoperative

S1 is the On/Off switch for the audible alarm only. The audible alarm will sound with an inoperative condition.

Figure 65. Aspirator alarm panel wiring

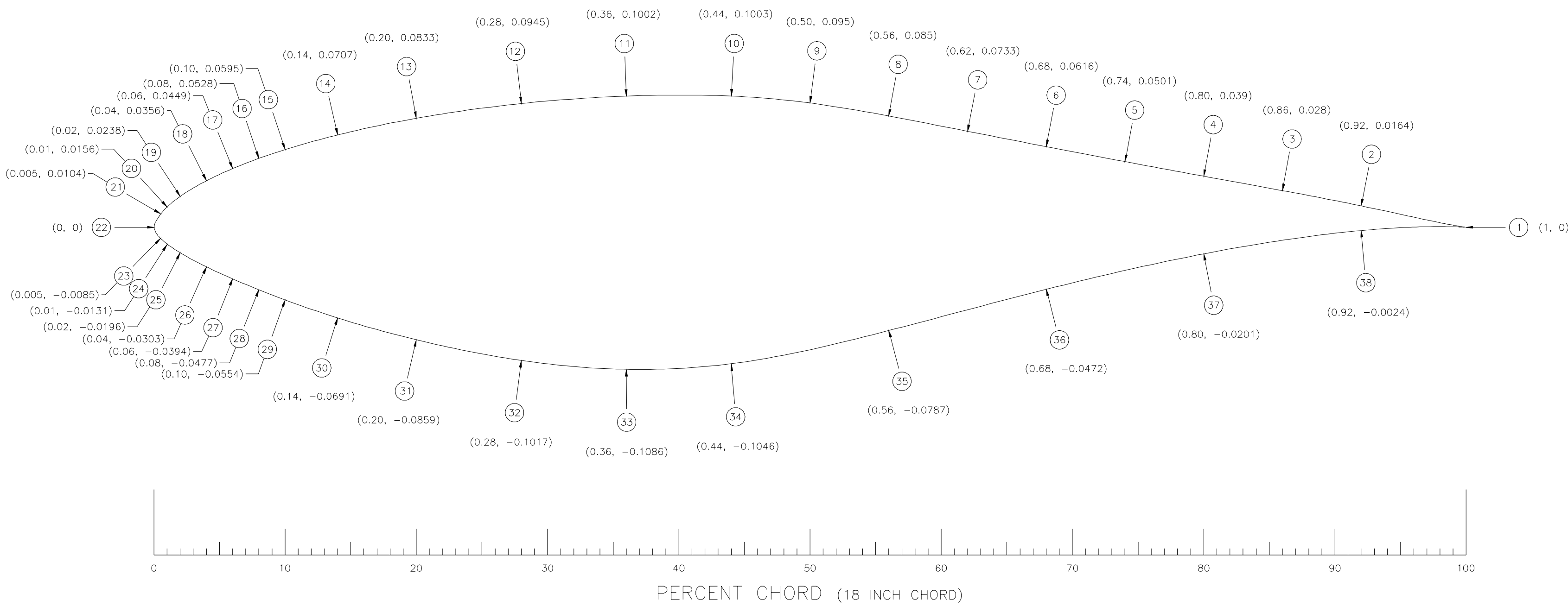


Figure 66. Pressure tap layout

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13. ABSTRACT *(Maximum 200 words)* The main objective of the Unsteady Aerodynamics Experiment is to provide information needed to quantify the full-scale, three-dimensional, unsteady aerodynamic behavior of horizontal-axis wind turbines (HAWTs). To accomplish this, an experimental wind turbine configured to meet specific research objectives was assembled and operated at the National Renewable Energy Laboratory (NREL). The turbine was instrumented to characterize rotating-blade aerodynamic performance, machine structural responses, and atmospheric inflow conditions. Comprehensive tests were conducted with the turbine operating in an outdoor field environment under diverse conditions. Resulting data are used to validate aerodynamic and structural dynamics models, which are an important part of wind turbine design and engineering codes. Improvements in these models are needed to better characterize aerodynamic response in both the steady-state post-stall and dynamic- stall regimes. Much of the effort in the first phase of the Unsteady Aerodynamics Experiment focused on developing required data acquisition systems. Complex instrumentation and equipment was needed to meet stringent data requirements while operating under the harsh environmental conditions of a wind turbine rotor. Once the data systems were developed, subsequent phases of experiments were then conducted to collect data for use in answering specific research questions. A description of the experiment configuration used during Phase V of the experiment is contained in this report.

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