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Technical Report

Unsteady Aerodynamics Experiment Phases II–IV Test Configurations and Available Data Campaigns

D.A. Simms, M.M. Hand,
L.J. Fingersh, D.W. Jager

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 aerodynamic behavior of horizontal axis wind turbines. 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 earlier 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 Phases II - IV 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 2-D wind tunnel airfoil test results. Blade designs are developed assuming steady loading optimization principles. While these design codes produce accurate predictions on average, instantaneous loads and peak power predictions are often incorrect. For horizontal axis wind turbines, 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, 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 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, low-speed shaft bending and torque, blade root bending, and tower motion, were obtained using various power transducers, accelerometers, and strain gages.

Two devices were used to obtain local flow characteristics in front of one of the three 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 last phase of the experiment to improve the dynamic response of the local flow angle measurement. Lastly, blade surface pressures were measured at one blade span location initially, 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 earlier phases of testing. A constant-chord optimally twisted blade set was used in later phases. Future tests are planned for a tapered and twisted blade set.

The Unsteady Aerodynamics Experiment was begun in 1987 (it was initially called the "Combined Experiment") and has been implemented in four phases to date. Phase I planning began in 1987 and resulted in valuable knowledge and experience with these types of measurements (Butterfield et al. 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 but the flow angle measurements were improved. The significant differences between the Phase II, Phase III, and Phase IV configurations are described in Table 1 below. This report follows the Phase I final report (Butterfield et al. 1992) to explain the evolution of these measurements from Phase II through Phase IV.

Table 1. Unsteady Aerodynamics Experiment Configuration Differences

	Phase II	**Phase III**	**Phase IV**
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
Blades	Untwisted	Twisted	Twisted
Local flow angle (LFA) measurement device	Flag	Flag, 5-Hole Probe (test)	5-Hole Probe
Span locations instrumented with LFA sensors	4	5	5
Span locations instrumented with full-chord pressure taps	4	5	5
Span locations instrumented with pairs of pressure taps	6	10	10
Azimuth angle measurements and RPM calculation	Poor	Good	Good
Meteorological instrumentation	Vertical Plane Array	Horizontal and Vertical Shear	Horizontal and Vertical Shear
Blade root strain gages	Yes	Yes	Yes
Blade strain gages	Yes	Yes	No
Blade tip and nacelle accelerometers	No	Yes	Yes
Selections of data during which yaw brake engaged	Yes	No	Yes
Campaign duration	5 minutes	10 minutes	10 minutes
Boom extension and camera mounted on hub; tufts on suction side of instrumented blade	Yes	No	Yes
Video	Yes	No	Yes

	Phase II	Phase III	Phase IV
Pitch angles (blade tip)	12°	3°, -3°, 8°	3°, -3°, 8°, 12°, -9°
File naming conventions: • **parked#, and d4pb###: Rotor brake engaged with instrumented blade at either 0° or 180° azimuth.** • **slwrot# and d4sr###: Blades feathered with rotor slowly rotating.** • **d4pp###: 'pp' indicates pitch angle** • **# indicates numerical order in which data collected**	d6511, d6512, d6521, d6522, d6611,…,d7521, d7522	data1-data19 parked1, parked2, slwrot1, slwrot2	data20-data112, slwrot4, slwrot5 d403001-d403039, d408001-d408012, d4m3001-d4m3012, d4pb001-d4pb009, d4sr001, d412001, d4m9001

This report is intended to provide the reader with information regarding the variations between phases of data collection. The instrumentation used in Phase II was presented by Butterfield et al. (1992), and is summarized in this report. Prior to Phase III, most of the instrumentation was replaced with newer components. The tables in the body of the report that describe the channels collected by the data system are based upon the header files that accompany each data campaign. Appendix A contains information detailing the turbine configuration differences between Phases II, III, and IV that could be used to develop models. Detailed descriptions and figures of each component of instrumentation used during Phases III and IV 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 two tables: one for Phase II and one for Phases III and IV. General atmospheric and turbine conditions are summarized in Appendix D for each phase of the experiment. Instrumentation failures and observations made during data collection are noted.

Test Facility Description

Location

All atmospheric testing was conducted at NREL's National Wind Technology Center 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 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 Unsteady Aerodynamics Experiment test turbine is a modified Grumman Wind Stream 33. It is a 10-m diameter, three-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-gaged link that measured yaw moments in Phase II and Phase IV. A mechanical caliper rotor brake system that could be operated manually from the control shed was also added. This feature was used to obtain data with the instrumented blade parked either behind the tower or at the top of the rotational cycle. A complete listing of turbine specifications may be found in Appendix A.

The drive train, pictured in Figure 1, 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 that is connected to the 20-kW induction generator. The inertia of the Phase IV rotor (twisted blades, instrumentation boxes, boom, hub, and camera) was determined by measuring low-speed shaft torque, power, and rotational speed during turbine startup. An estimate of drive train (low-speed shaft, gearbox, and high-speed shaft) stiffness was also obtained from this test. The inertia of the entire rotating system (rotor and drive train) was measured with a pendulum 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.

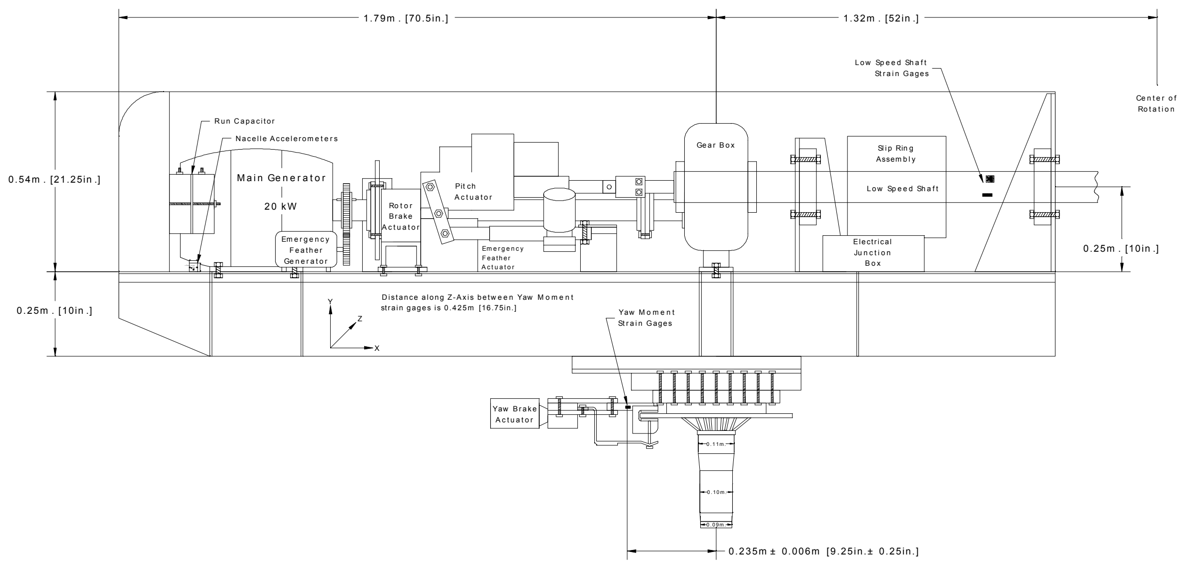


Figure 1. Drive-train configuration.

The most 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 data base that included pressure distributions, separation boundary locations, drag data, and flow-visualization data (Somers 1997, Butterfield et al. 1992). This airfoil was used in both the untwisted and twisted blade configurations which are pictured in Figures 2 and 3, respectively.

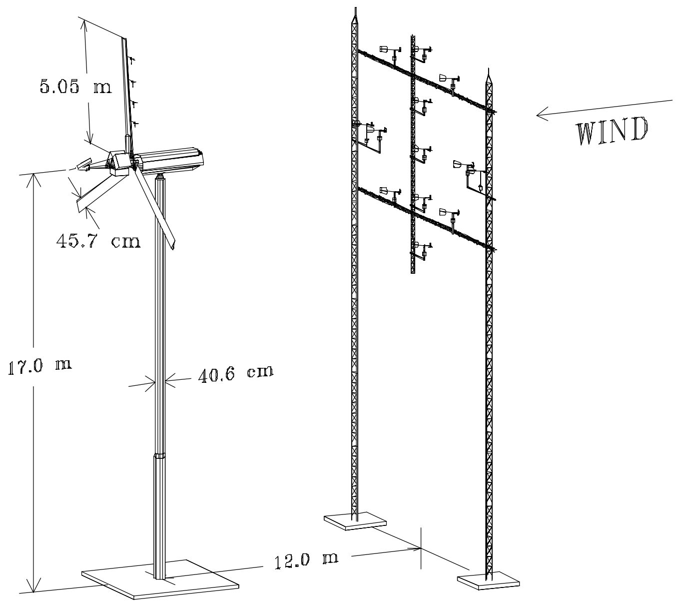


Figure 2. Phase II test configuration. The prevailing wind direction is 292° from true north.

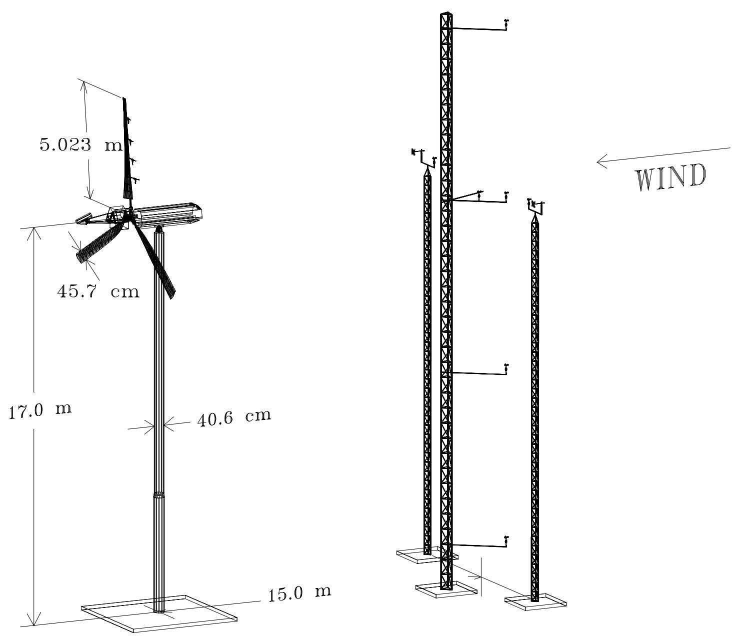


Figure 3. Phase III and Phase IV test configuration. The prevailing wind direction is 292° from true north.

The untwisted and twisted blades were similar in design and fabrication. Both had a constant 0.457-m chord, and a planform view of the blades is shown in Figure 4. 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 of the blades used in Phases III and IV is listed in Appendix A and shown in Figure 5. The root thickness and airfoil distribution of the twisted blades were nearly identical to that of the untwisted blades with the spar enlargement extending to 25% span instead of 30% span. Both sets of blades were fiberglass/epoxy composite, but the spar in the twisted blades was carbon fiber as opposed to the fiberglass/epoxy spar used in the untwisted blades. 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.

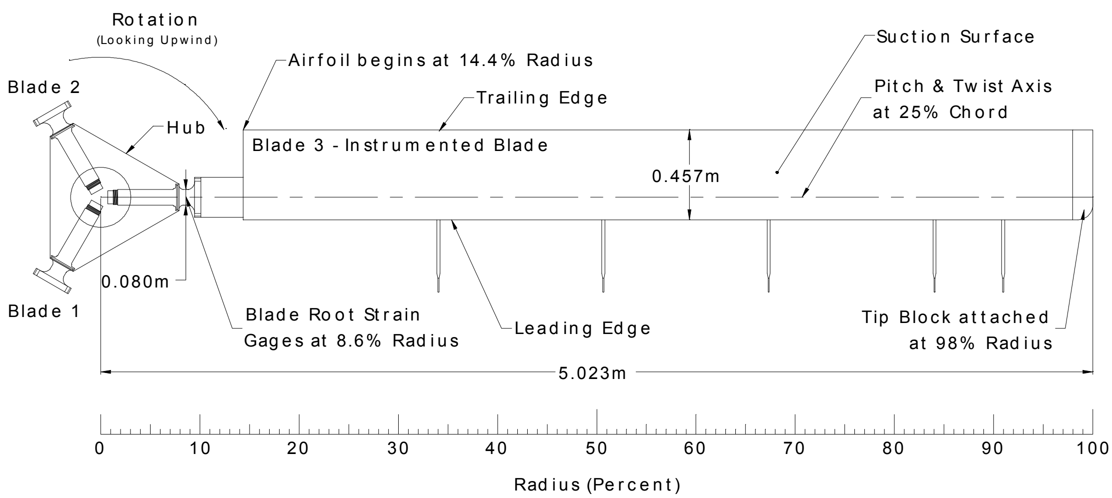


Figure 4. Twisted blade planform.

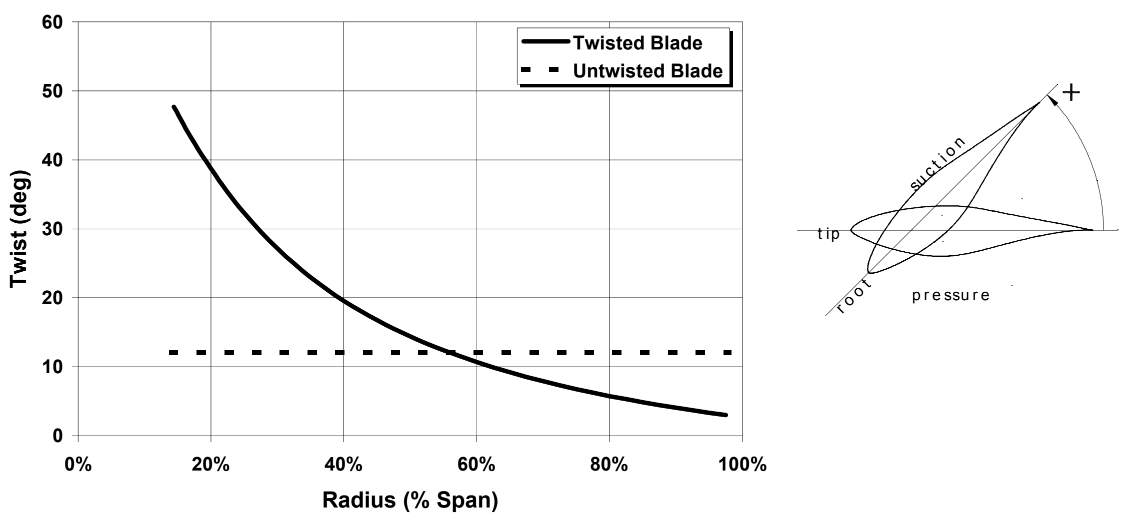
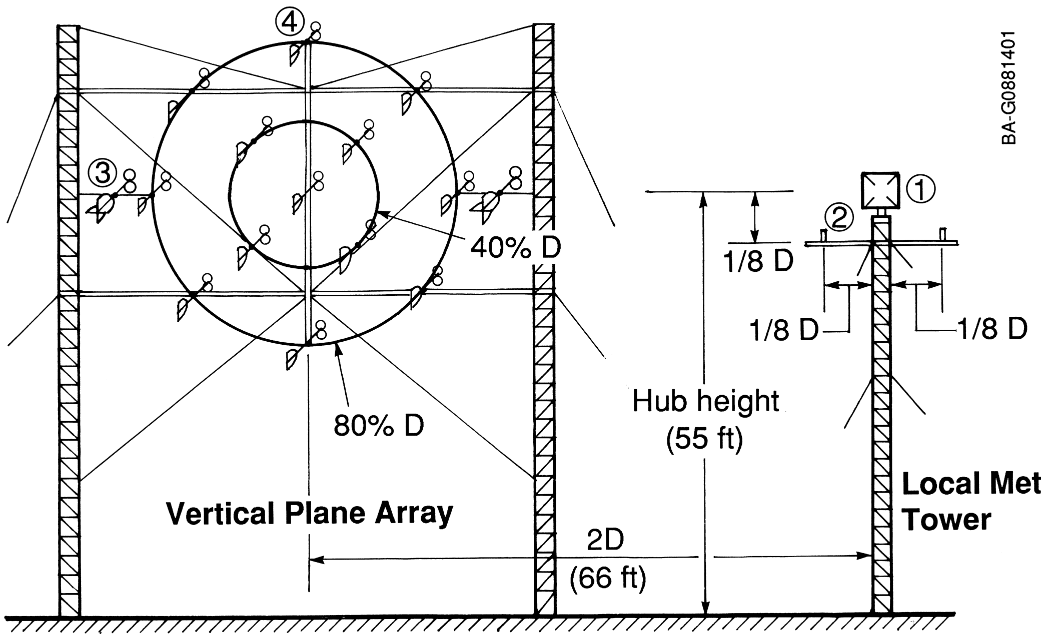


Figure 5. Blade twist distribution at the pitch setting used most frequently during experiment data acquisition: 12° for Phase II and 3° (at tip) for Phases III and IV

INSTRUMENTATION

Meteorological (MET) Towers

During Phase II, the inflow conditions were measured at three locations in the predominant upwind direction (292°): the north met tower, the local met tower, and the vertical plane array (VPA). The north met tower was 50 m tall and located 500 m upwind of the turbine. Large-scale atmospheric boundary-layer conditions were measured at this location in the form of wind speed and direction at four elevations (5 m, 10 m, 20 m, and 50 m), temperature at 5 m and at 50 m, and barometric pressure. Local inflow measurements were made 12 m upwind of the turbine on the VPA which is depicted in Figure 6. Two Rohn 45-G guyed met towers supported three cross-booms, where 11 prop-vane and 2 bi-vane anemometers measured inlet flow magnitude and direction. Eight of the prop-vane anemometers were arranged in a circle corresponding to 80% of the blade span at about hub height, 17 m. The remaining prop-vane anemometers were spaced evenly inside the circle. The two bi-vane anemometers were mounted outside the circle on the horizontal axis. Also located 12 m upwind of the turbine and 20 m to the north was the 16.8 m local met tower. Sonic anemometer measurements originated from this tower. Detailed discussion of the anemometry used in the Phase II portion of the experiment appears in Butterfield et al. (1992). Table 2 lists all of the channels related to measurements made on the Phase II met towers.



Item No.	Description	Quantity
1	U-V-W sonic anemometer	1
2	Ruggedized hot films	2
3	Bi vane anemometers	2
4	Prop vane anemometers	13

Figure 6. Phase II (Untwisted Blade) Meteorological Instrumentation. Elevation view looking downwind toward 112°. Meteorological instruments are 1.2 D (12 m) upwind of the turbine tower.

Table 2. Phase II (Untwisted Blade) Local Inflow Measurements

Channel	Channel ID	Description	Units
038	VPAWS1	VPA Prop Vane Speed WS-1 (12:00)	m/s
039	VPAWS2	VPA Prop Vane Speed WS-2 (1:30)	m/s
040	VPAWS3	VPA Prop Vane Speed WS-3 (3:00)	m/s
041	VPAWS4	VPA Prop Vane Speed WS-4 (4:30)	m/s
042	VPAWS5	VPA Prop Vane Speed WS-5 (6:00)	m/s
043	VPAWS6	VPA Prop Vane Speed WS-6 (7:30)	m/s
044	VPAWS7	VPA Prop Vane Speed WS-7 (9:00)	m/s
045	VPAWS8	VPA Prop Vane Speed WS-8 (10:30)	m/s
046	VPAWS9	VPA Prop Vane Speed WS-9 Hub Height	m/s
047	VPAWD9	VPA Prop Vane Direction WD-9 Hub Height	deg
048	VPAWS12	VPA Bi-Vane Speed WS-12 (3:00 @100%)	m/s
049	VPAWD12	VPA Bi-Vane Direction WD-12 (3:00 @100%)	deg
050	VPAWE12	VPA Bi-Vane Elevation WE-12 (3:00 @100%)	deg
051	VPAWS13	VPA Bi-Vane Speed WS-13 (9:00 @100%)	m/s
052	VPAWD13	VPA Bi-Vane Direction WD-13 (9:00 @100%)	deg
053	VPAWE13	VPA Bi-Vane Elevation WE-13 (9:00 @100%)	deg
054	VPAWS10	VPA Prop Vane Speed WS-10 (12:00 @40%)	m/s
055	VPAWS11	VPA Prop Vane Speed WS-11 (6:00 @40%)	m/s
102	LMSA17M	Sonic Anemometer Channel A	m/s*
103	LMSB17M	Sonic Anemometer Channel B	m/s*
104	LMSC17M	Sonic Anemometer Channel C	m/s*
300	NMWD5M	North Met Wind Direction 5 m	deg*
301	NMWS5M	North Met Wind Speed 5 m	m/s
302	NMWD10M	North Met Wind Direction 10 m	deg*
304	NMWD20M	North Met Wind Direction 20 m	deg
305	NMWS20M	North Met Wind Speed 20 m	m/s
306	NMWD50M	North Met Wind Direction 50 m	deg
307	NMWS50M	North Met Wind Speed 50 m	m/s
308	NMT5M	North Met Temperature 5 m	degC
309	NMDT	North Met Delta Temperature T50-T05	degC
310	BARO	Barometric Pressure	Pa

* These channels do not appear in all campaigns.

Inflow conditions were again measured directly upwind of the turbine during Phases III and IV, but the north met tower was not used. Instead, a taller local met tower was used to measure shear and stability near 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. The cup anemometers provided more accurate wind speed measurements than the prop-vane anemometers used during Phase II because the cup anemometers have a higher frequency response and are not susceptible to gyroscopic effects. Temperature and barometric pressure measurements were also made. Figure 7 shows the three, instrumented, met towers. Phase III and Phase IV meteorological channel descriptions are shown in Table 3 and detailed instrumentation and wiring information is presented in Appendix B.

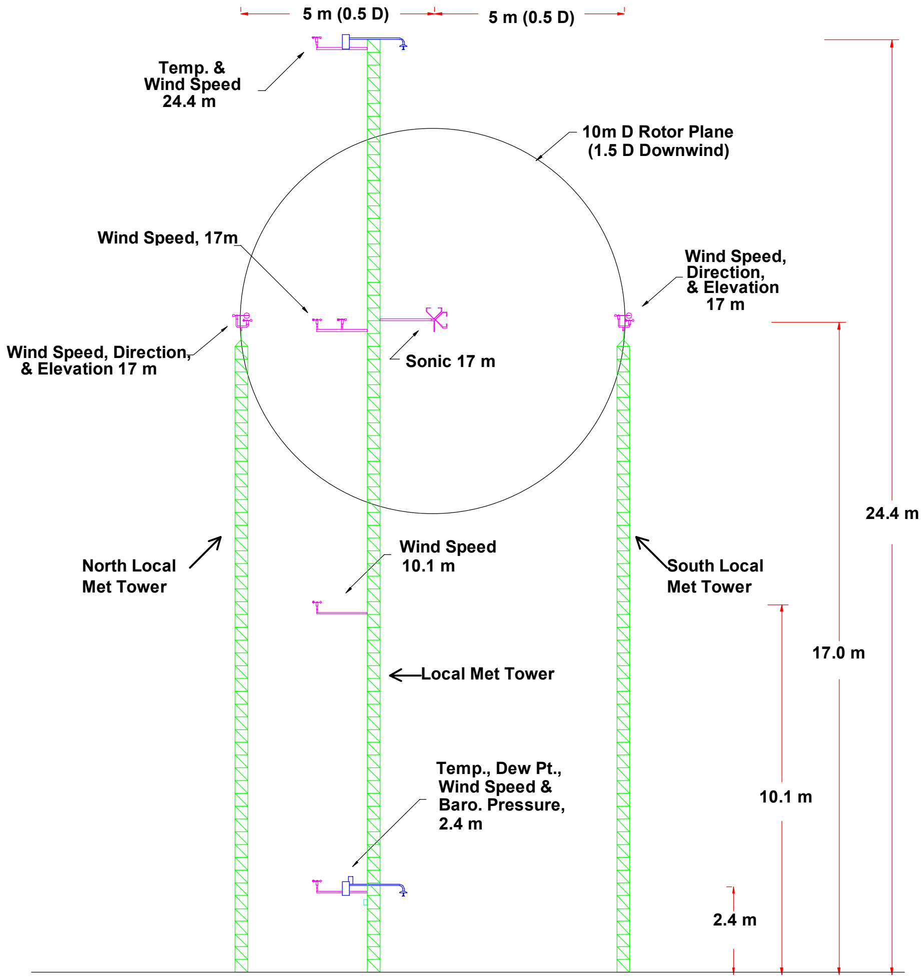


Figure 7. Phase III and Phase IV (twisted blade) meteorological instrumentation. Elevation view looking downwind toward 112°. Meteorological instruments are 1.5 D (15 m) upwind of the turbine tower.

Table 3. Phase III and Phase IV (Twisted Blade) 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 2.4m	degC
322	LMDT	Local Met Delta Temperature	degC*
322	LMT24M	Local Met Temperature 24.38 m	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

* These channels do not appear in all campaigns.

Pressure Measurements

Pressure Probes

A Kiel pitot probe attached to the local flow angle flag pictured in Figure 8 measured dynamic pressure during Phases II and III. The Kiel pitot probe configuration provides total pressure measurement over a wider range of angle of attack than conventional pitot probes. To prevent flow disturbance, the probe extended 0.64 m (0.62 m during Phase II) ahead of the leading edge along the chord line of the airfoil and was mounted 4% outboard of each primary pressure station (30%, 47%, 63%, and 80%). The probe was mounted at 86% span instead of 84% span during Phase II. To maximize the probes' effectiveness, the probe tips were bent about 20° below the chord line as shown in Figure 8, so the measurement range would coincide with the nominal operating angle of attack. Each probe was connected to a pressure transducer via 1.5875 mm outer diameter (0.6731 mm inner diameter) stainless steel tubing. A short piece of plastic tubing was used to join the tubes to the transducer. The probes measured the difference between the stagnation and reference pressures with less than 10% error for inflow angles between -40° and 40° (Huyer 1993). The channels associated with the Phase II probe pressure measurements appear in Table 16 with the stagnation pressure channels.

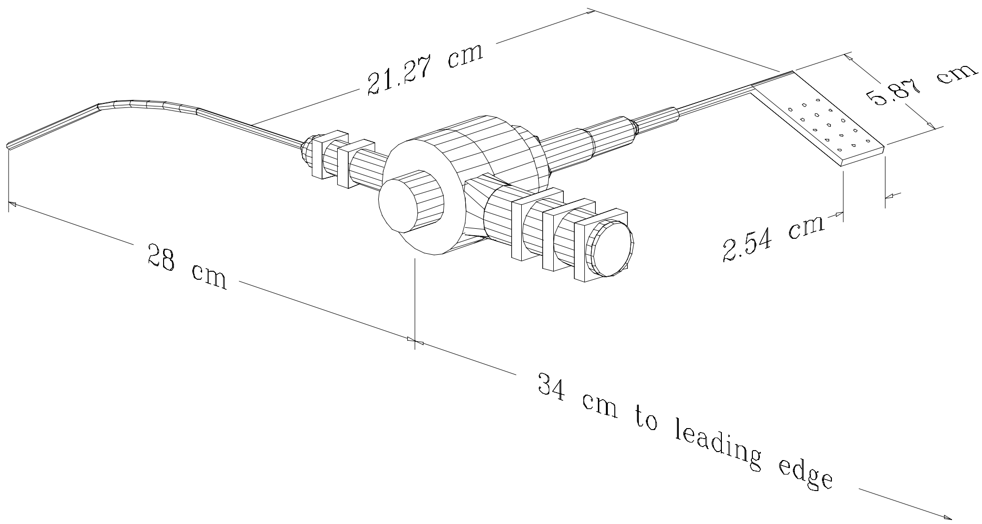


Figure 8. Local flow angle flag and total pressure probe assembly used during Phase II and Phase III.

During Phase IV the 5-hole probe shown in Figure 9 provided a dynamic pressure measurement 0.37 m ahead of the leading edge at an angle of 20° below the chord line. The 5-hole probes were mounted in the same locations as the pitot probes with the addition of one at 91% span. The pressure channels associated with each of the five holes are listed in Table 4. 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° 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 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. The surfaces were implemented as look-up tables in the post-processing code. An iterative solution was developed to determine the probe total pressure measurement, and bi-linear interpolation was used to obtain all three measurements from their respective surfaces (Fingersh and Robinson 1997). The span-wise flow angle and local flow angle channels appear in Table 10 and the dynamic pressure measurements appear in Table 16. A single, 5-hole probe mounted at 91% span was tested during Phase III. This probe extended 0.34 m ahead of the leading edge of the blade and was aligned with the chord. As a result of the satisfactory performance, all of the flag devices were replaced with 5-hole probes for Phase IV testing.

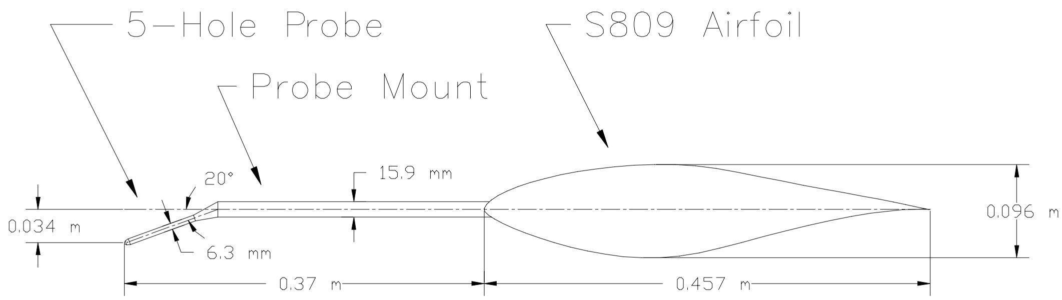


Figure 9. Blade mounted 5-Hole probe (During Phase III the test probe at 91% span extended 0.34 m in front of the blade aligned with the chord, not declined 20°).

Table 4. Phase III and IV 5-Hole Probe Pressures

Channel	Channel ID	Description	Units
052, 053, 152, 153, 252	5HC34, 5HC51, 5HC67, 5HC84, 5HC91, 5HC90*	5-hole Center Port 1 (34%, 51%, 67%, 84%, and 91% span)	Pa
054, 055, 154, 155, 254	5HL34, 5HL51, 5HL67, 5HL84, 5HL91, 5HL90*	5-hole Lower Port 2 (34%, 51%, 67%, 84%, and 91% span)	Pa
056, 057, 156, 157, 256	5HU34, 5HU51, 5HU67, 5HU84, 5HU91, 5HU90*	5-hole Upper Port 3 (34%, 51%, 67%, 84%, and 91% span)	Pa
058, 059, 158, 159, 258	5HO34, 5HO51, 5HO67, 5HO84, 5HO91, 5HO90*	5-hole Outboard Port 4 (34%, 51%, 67%, 84%, and 91% span)	Pa
060, 061, 160, 161, 260	5HI34, 5HI51, 5HI67, 5HI84, 5HI91, 5HI90*	5-hole Inboard Port 5 (34%, 51%, 67%, 84%, and 91% span)	Pa

* Phase III channel ID incorrectly lists the single 5-hole probe at 90% span

The probe was not rotated to the appropriate angle for one of the runs during the wind tunnel calibration of the probe that was mounted at 51% span,. This was not discovered until the first portion of Phase IV (data20-data112, slwrot4, and slwrot5) had been completely processed. 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 Phase IV data obtained in 1997.

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 1.5875 mm (0.6731 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 (0.6731 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 10, the taps were concentrated toward the leading edge to achieve increased resolution in the more active areas of the pressure distributions.

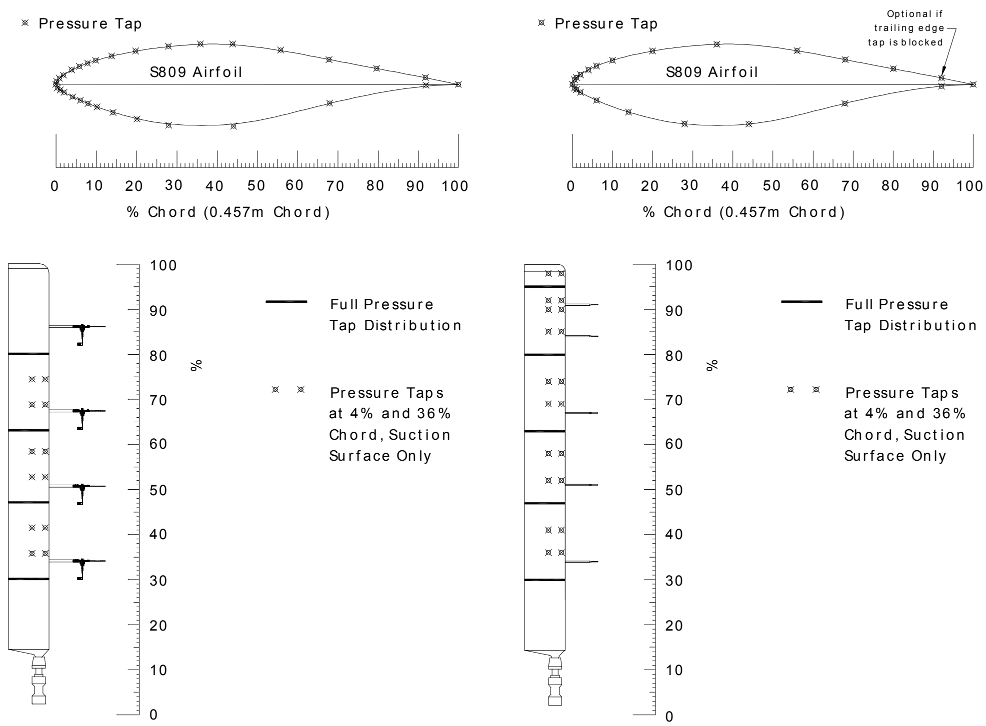


Figure 10. Configuration of Phase II (untwisted) instrumented blade and Phase IV (twisted) instrumented blade. During Phase III, the local flow angle flags were used at the four inboard flow angle stations, and a 5-hole probe was tested at 91% span. The pressure tap configuration was identical to that used during Phase IV.

The Phase II experiment used 28 of the 38 pressure taps at four primary radial locations: 30% span, 47% span, 63% span, and 80% span. Table 5 describes the pressure tap locations used during Phase II. During Phases III and IV, 22 of the 38 taps were instrumented at five primary span-wise locations: 30% span, 47% span, 63% 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%). These channels are listed in Table 6. The correlation between pressure tap number and airfoil chord location is shown in Table 7. Figure 10 depicts the blade layout for Phases II and IV. The Phase III blade layout differed from the Phase IV layout in that the local flow angle flag assemblies were mounted at the four inboard primary span locations instead of the 5-hole probes. Also the 5-hole probe mounted at 91% span was aligned with the chord line, not bent into the dominant flow direction as was done for the probes used during Phase IV.

Table 5. Phase II Pressure Tap Locations

Channel	Channel ID	Description	Units
002-029	Ptt63ccc	Surface Pressure Coefficients at 63% Span tt = Pressure Tap Number (1, 2, 4, 6, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 28, 30, 32, 34, 36, 38)	Pa
124-151	Ptt80ccc	Surface Pressure Coefficients at 80% Span tt = Pressure Tap Number (1, 2, 4, 6, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 25, 26, 27, 28, 30, 32, 34, 36, 38)	Pa
200-224	Ptt30ccc	Surface Pressure Coefficients at 30% Span tt = Pressure Tap Number (1, 4, 6, 8, 10, 11, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 28, 30, 31, 34, 36, 38)	Pa
229-256	Ptt47ccc	Surface Pressure Coefficients at 47% Span tt = Pressure Tap Number (1, 2, 4, 6, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 25, 26, 27, 28, 30, 32, 34, 36, 38)	Pa
000, 001, 030-032, 152-154, 225-227, 257	P18ss04U P11ss36U	Surface Pressure Coefficients at 36%, 41%, 52%, 58%, 69%, and 74% Span Pressure Tap Number (11, 18)	Pa

Table 6. Phase III and Phase IV Pressure Tap Locations

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,	Pa
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,	Pa
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,	Pa
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,	Pa
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,	Pa
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.	Pa

Table 7. 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

* See Tables 5 and 6

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 et al. 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 40 Hz, and the measured pressure spectra of a typical data set showed no appreciable information above 40 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 because of rotational effects, so transducers with different measurement ranges were used. The nominal transducer ranges used during different test phases are listed below in Table 8. The transducers, Pressure Systems Inc. (PSI) model ESP-32, scanned 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 (local static pressure). 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 reference tube. 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 8. Nominal, Full-scale, Pressure Transducer Measurement Ranges

	Phase II	Phase III and Phase IV
30% Span	± 2970 Pa (0.4 psi)	± 2488 Pa (10" H_2O)
47% Span	± 2970 Pa (0.4 psi)	± 2488 Pa (10" H_2O)
63% Span	± 8274 Pa (1.2 psi)	± 4977 Pa (20" H_2O)
80% Span	± 8274 Pa (1.2 psi)	± 10,342 Pa (1.5 psi)
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 source 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 source 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. During Phase III and the first season of Phase IV (1996), heaters in the instrumentation packages were thermostatically controlled to prevent condensation inside the boxes. When the heaters cycled on and off, the static pressure in the box changed significantly affecting all of the measured pressures. The portions of each campaign affected by the heaters are noted in Appendix D. During the second season of Phase IV data collection (1997), the heaters were turned off during data collection.

The hub-mounted instrumentation boxes used during Phases III and IV differed from those used during Phase II. As described above, the Phase III and IV box reference pressure was vented to the atmosphere on the upwind side. During Phase II, the box was sealed as tightly as possible. 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 and IV data showed that the box reference pressure varied significantly from static pressure. Subsequent direct measurement confirmed the result. Therefore, all pressure measurements should be corrected for this reference pressure offset. This correction is described in the "Reference Pressure Correction" section below, and will be further addressed in subsequent reports.

Because of the rotation of the reference pressure line, centrifugal forces acting on the column of air contained in the tube change the pressure along the radius of the blade. Each measurement was corrected for centrifugal force effects and normalized with the blade stagnation pressure as described in the Engineering Unit Conversion section that follows. No correction for hydrostatic pressure variation has been applied, but one has been suggested by Corten, 1998.

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 et al. 1992). The PSC was completely redesigned from Phase II to Phase III 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 et al. 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.

Local Flow Angle (LFA) Transducers

Geometric angle of attack (AOA) measurements are fairly easy to make in a wind tunnel where the air flow is precisely controlled. It is significantly more difficult to quantify AOA on a rotating blade in the field. This is in part because of widely varying environmental factors such as dynamic inflow, turbulence, wind shear, and yawed operation. It is additionally complicated by blade upwash due to bound vorticity, AOA measurement device effects on airfoil performance, and 3-D flow effects in the rotating environment. Based on these considerations, it is highly unlikely that a measurement parameter equivalent to 2-D AOA can be made in the 3-D operating environment. Therefore, LFA measurements were made instead as an attempt to provide an approximation or estimation of the inflow angle.

The LFA sensor illustrated in Figure 8 was developed by NREL for this purpose (Butterfield et al. 1992) and was used in Phase II and Phase III tests. It consisted of a lightweight, rigid flag that aligned itself with the local flow. During Phase II tests, a commercial rotary position sensor mounted in a custom housing measured the flag angle within ±1.0° accuracy over the range of -20° to 40°. The analog signals generated were sent to the hub, multiplexed, and recorded with the other signals by the data acquisition system. This analog position encoder was replaced with a digital resolver during Phase III testing to increase measurement accuracy. The flag extended 36 cm (34 cm during Phase II) ahead of the leading edge and was aligned with the pressure taps. The sensor was attached to the blade 4% outboard of the four primary pressure stations (30%, 47%, 63%, and 80%) in order to minimize flow disturbances on the blade near the pressure taps.

During Phase II the flag sensor was actually mounted at 86% span measuring a local flow angle at 82% span instead of 80% span. However, in Phase II testing, this local flow angle is associated with the 80% span pressure tap location. Processing of the data revealed that during Phase II the flag at 47% span did not work properly for most of the duration of testing so it was removed from the processed data files. The following table describes the local flow angle measurements for Phase II and Phase III. Additional information concerning the digital resolver used during Phase III may be found in Appendix B.

Table 9. Phase II and Phase III Local Flow Angle Measurements (Flag)

Channel	Channel ID	Description	Units
034 (II), 249 (III	80LFA	80% Span Local Flow Angle (Flag)	deg*
035 (II), 247 (III	63LFA	63% Span Local Flow Angle (Flag)	deg
245 (III)	47LFA	47% Span Local Flow Angle (Flag)	deg
037 (II), 243 (III	30LFA	30% Span Local Flow Angle (Flag)	deg

* Actually measured LFA at 82% span during Phase II.

During Phase III, a 5-hole probe was mounted 4% inboard of the 95% span pressure station in order to test this device for measuring local flow angle. The probe was designed to measure angles in the range ±45°. Because the probe was mounted parallel to the chord line of the blade, it was not within this prescribed measurement range for many operating conditions. For this reason, these data should be regarded with discretion, but the test did prove that the five hole probe provided greater dynamic response than the flag which is necessary in studying dynamic stall (Fingersh and Robinson 1997). Therefore all of the flag sensors were replaced with five hole probes during Phase IV testing. The probes, depicted in Figure 9, extended 37 cm ahead of the leading edge at an angle about 20° below the chord line and measured local flow angles over the range from -15° to 55°. They were mounted 4% span outboard of the primary pressure stations except at the 95% pressure tap station where the probe was mounted 4% span inboard. The local flow angle measurement from the probe is no longer aligned with the full-chord pressure measurements as was the local flow angle measured with the flag. Thus blade twist and rotational effects are introduced. In addition to the local flow angle, the 5-hole probes used in Phase IV provided measurement of the span-wise flow angle. The following table describes the local flow angle measurements made during Phase IV.

Table 10. Phase IV Local Flow Angle Measurements (5-Hole Probe)

Channel	Channel ID	Description	Units
853	5HP34A	5Hole 34% Local Flow Angle (Angle of Attack)	deg
856	5HP51A	5Hole 51% Local Flow Angle (Angle of Attack)	deg
859	5HP67A	5Hole 67% Local Flow Angle (Angle of Attack)	deg
862	5HP84A	5Hole 84% Local Flow Angle (Angle of Attack)	deg
865	5HP91A	5Hole 91% Local Flow Angle (Angle of Attack)	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

Strain Gages and Accelerometers

Blade, tower, rotor, and yaw loads were measured with strain gages during Phase II testing. Six span-wise locations on the instrumented blade, root (8% span), 20% span, 40% span, 50% span, 70% span, and 90% span, were instrumented with strain gages to measure blade flap-wise bending while two locations, root (8% span) and 50% span, were instrumented to measure edge bending. Blade pitching moment (blade torsion) was measured at the root (8% span), 50% span and 70% span. Root flap and edge bending moments were also measured on the other two blades. Bending of the low speed shaft in two orthogonal planes was measured as well as the low speed shaft torque. Loads in the non-rotating environment were also measured. Gages were mounted on two tower bending axes at the point just above the guy wire attachment. These gages were oriented to measure bending parallel and perpendicular to the direction of the prevailing wind. Gages were mounted on the arm of the yaw brake to measure yaw moment when the yaw brake was engaged. All load measurements corresponding to Phase II tests are listed in Table 11. Estimates of thrust and torque derived from aerodynamic forces as described in the Engineering Unit Conversion section were also included in Table 11.

Table 11. Phase II (Untwisted Blades) Load Measurements

Channel	Channel ID	Description	Units
57	YAWMOM	Yaw Moment	N-m
58	TBEWAX	Tower Bending about East-West Axis (X)	N-m
59	TBNSAY	Tower Bending about North-South Axis (Y)	N-m
105	B3ARFB	Strain Blade 3A, Root Flap Bending	N-m
106	B3BRFB	Strain Blade 3B, Root Flap Bending (duplicate)	N-m
107	B1RFB	Strain Blade 1, Root Flap Bending	N-m
108	B2RFB	Strain Blade 2, Root Flap Bending	N-m
109	B320FB	Strain Blade 3, 20% Flap Bending	N-m
110	B340FB	Strain Blade 3, 40% Flap Bending	N-m
111	B350FB	Strain Blade 3, 50% Flap Bending	N-m
112	B370FB	Strain Blade 3, 70% Flap Bending	N-m*
113	B390FB	Strain Blade 3, 90% Flap Bending	N-m
114	B3AREB	Strain Blade 3, Root Edge Bending	N-m
115	B320EB	Strain Blade 3, 20% Edge Bending	N-m
116	B350EB	Strain Blade 3, 50% Edge Bending	N-m
117	70TQ	70% Blade Torque	N-m*
118	RTTQ	Root Torque (link)	N-m
119	50TSN	Blade 3 Torsion at 50% Span	N-m
120	LSSXXB	Strain X-X LSS Bending	N-m
121	LSSYYB	Strain Y-Y LSS Bending	N-m
122	LSSTQA	Strain LSS Torque A	N-m
123	LSSTQB	Strain LSS Torque B (duplicate channel)	N-m
813	EAEROTH	Thrust	N
814	EAEROTQ	Torque	N-m

* These channels do not appear in all campaigns.

Similar measurements were made during Phase III and IV testing periods. Flap and edge bending moments were recorded from strain gages mounted at the root (8.6% span), 25%, and 60% span on the instrumented blade. Flap and edge bending measurements were acquired at the root of the other two blades, and low speed shaft bending in two planes as well as low speed shaft torque measurements were also obtained. There were no pitching moment measurements made in either of these phases of the experiment. Instead of measuring tower bending with strain gages, 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. During Phase IV, strain gages were used to measure yaw moment when the yaw brake was applied. A relatively constant yaw angle and non-zero, fluctuating, yaw moment indicates the yaw brake was engaged during data acquisition. These measurements are listed in Table 12, and a description of the instrumentation is presented in Appendix B.

Table 12. Phase III and Phase IV (Twisted Blade) 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*
205	B2ACFL	Accelerometer Blade 2-Flap	m/s^2*
207	B2ACED	Accelerometer Blade 2-Edge	m/s^2*
209	B3ACFL	Accelerometer Blade 3-Flap	m/s^2*
211	B3ACED	Accelerometer Blade 3-Edge	m/s^2*
215	B325FB	Strain Blade 3 25% Flap Bending	N-m*
217	B325EB	Strain Blade 3 25% Edge Bending	N-m*
219	B360FB	Strain Blade 3 60% Flap Bending	N-m*
221	B360EB	Strain Blade 3 60% Edge Bending	N-m*
225	B1RFB	Strain Blade 1 Root Flap Bending	N-m*
227	B1REB	Strain Blade 1 Root Edge Bending	N-m*
229	B2RFB	Strain Blade 2 Root Flap Bending	N-m
231	B2REB	Strain Blade 2 Root Edge Bending	N-m
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*
813	EAEROTH	Thrust	Nt
814	EAEROTQ	Torque	Nt-m

* These channels do not appear in all campaigns.

During all phases of testing, strain gages 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% (8% for Phase II) span, the location where the strain gages 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 4 as well as in Appendix B.

Strain gages on the instrumented blades consisted of four active gage elements mounted inside the fiberglass blade skin. The gages were installed inside the skin during the blade manufacturing process to preserve the exterior airfoil shape and surface smoothness. The strain gages were positioned carefully to minimize flap-wise and edge-wise cross talk. A maximum of 4% cross talk was measured during the blade pull and strain gage calibration tests (Butterfield et al. 1992). These cross-channel interference effects were not considered significant, and corrections were not applied to the data.

Miscellaneous Transducers

Various sensors were used to measure yaw position, pitch angle, and rotor azimuth position. In Phase II, gear-driven potentiometers were used to measure yaw position and pitch angle of the instrumented blade. The rotor azimuth position was measured with an analog rotary position encoder connected to the low-speed shaft via a gear and chain. This device created discontinuities and non-linearities because of its physical limitations in the transition from 0° to 360°. The data were therefore corrected during post-processing through insertion of an idealized saw-tooth between adjacent 180° transition points. This provided a clean transition from 0° to 360° and smooth linear values throughout the rest of the cycle. However, the rotational frequency channel (RPM), calculated during post-processing, was affected by this smoothing of the data so it must be regarded with speculation. Occasionally, the 180° transition points were not properly identified resulting in two rotations fit with one wave or two waves fit to one blade rotation. Those cycles with this problem are listed in Appendix E.

During Phases III and IV, gear-driven, BEI model R-25 optical absolute position encoders replaced the gear-driven potentiometers measuring yaw position and pitch angle, and each of the blades was given an encoder for pitch measurements. The azimuth angle measurement was made digitally, and the errors induced in Phase II were not applicable to subsequent testing. The fluctuations in blade pitch angle are attributed to excessive compliance in the pitch mechanism that sets the blade angles.

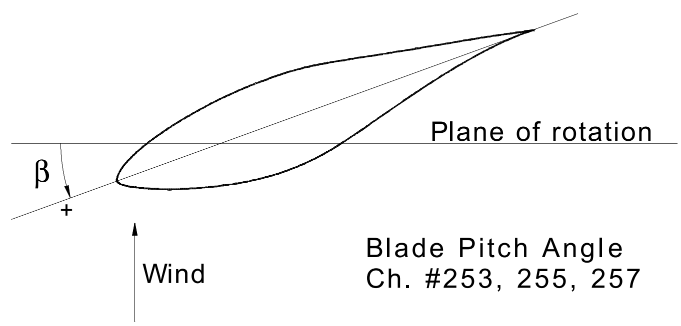
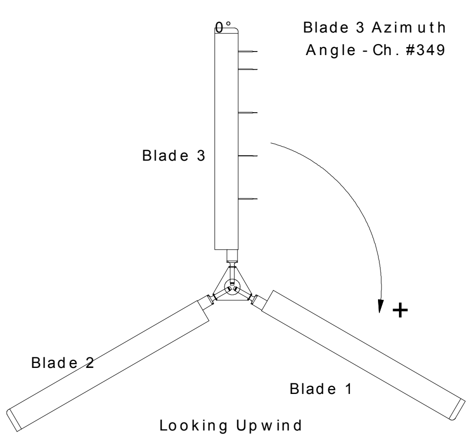


Figure 11. Blade pitch angle orientation.



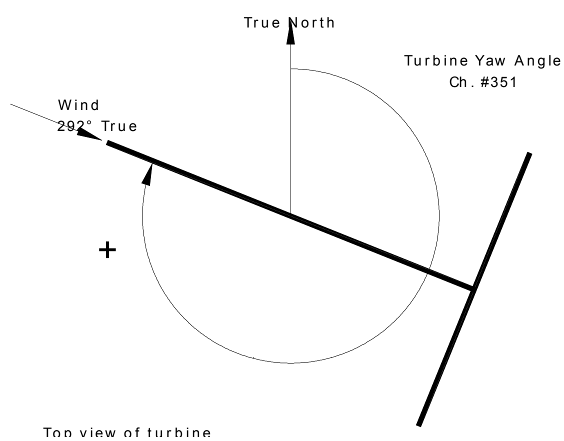


Figure 12. Blade azimuth angle convention. **Figure 13. Yaw angle convention.**

During Phase II testing, a barometer was placed within the PSC container to measure the atmospheric pressure to which all of the transducers were referenced. It was later determined that the resolution of the barometer was not fine enough to accurately measure the reference pressure. This measurement was not duplicated in Phases III and IV.

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 13 below and fully described in Appendix B.

Table 13. Phase II, Phase III, and Phase IV Miscellaneous Transducers

Channel	Channel ID	Description	Units
253 (III&IV)	B1PITCH	Digital Blade 1 Pitch	deg*
255 (III&IV)	B2PITCH	Digital Blade 2 Pitch	deg*
157 (II), 257 (III&IV)	B3PITCH	Digital Blade 3 Pitch	deg
61 (II), 332 (III&IV)	GENPOW	Generator Power	kW
56 (II), 349 (III&IV)	B3AZI	Blade 3 Azimuth Angle	deg
60 (II), 351 (III&IV)	YAW	Yaw Angle	deg
311 (II), 353 (III&IV)	DAY	Clock - Day	day
312 (II), 355 (III&IV)	HOUR	Clock - Hour	hour
313 (II), 357 (III&IV)	MINUTE	Clock - Minute	minute
314 (II), 359 (III&IV)	SECOND	Clock - Second	second
315 (II), 361 (III&IV)	MILLISEC	Clock - Millisecond	msec
156 (II)	ABSRP	Absolute Reference Pressure	Pa #

* Phase III and Phase IV only.

Phase II only

Flow Visualization

Cameras

Two high-shutter speed cameras were mounted in the rotating frame during Phase II and Phase IV testing. 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. During all three phases of testing 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 during Phases III and IV. However, during Phase II, the blades were balanced before the camera was mounted. Additional equipment, such as the data acquisition system, the PSC, and lighting for night testing, was also mounted on the hub. Variations in the mass of the hub due to combinations of this equipment for each phase of the experiment are noted in Appendix A.

Tufts

Flow visualization was achieved through the use of tufts attached to the surface of the blade during Phase II and Phase IV testing. 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. During Phase II, tufts were placed in rows spaced 76 mm apart in the span-wise direction. In each row, the tufts were spaced every 10% of the chord. The tufts on the leading edge and at 10% chord were intentionally omitted during Phase II testing to avoid blade roughness effects that might have been created by the tufts themselves. This was deemed unnecessary during Phase IV tests so 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. 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 during Phase II testing. Thus, night testing was preferred. Also the black color of the blade that was chosen to enhance the contrast of the tufts caused differential heating of the blade surfaces during the day which led to a thermal drift problem with the blade strain gages. In order to collect data at night, eleven tungsten-halogen, 120-V spotlights were placed along the camera boom and directed at the blade. With this configuration, the video pixel intensity of a tuft was 35 on a gray scale of 0 to 245, and the black background was 10 to 15; the contrast was great enough so that the tufts could be seen easily (Butterfield et al. 1992). Unfortunately, there was still not enough light to operate the camera shutter, and moving images were blurred on the video display.

Most tests were performed in daylight during Phase IV, but the contrast between the tufts and the blade was sufficient, especially under cloudy skies. For night testing, 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. These powerful bulbs illuminated the tufts so that the video images are much clearer than those obtained during Phase II.

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 (during Phase II, one PCM stream corresponding to the North Met tower instrumentation originated at the tower, and one PCM stream corresponding to the Local Met tower instrumentation originated in the data shed). 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 Combined Experiment (Butterfield et al. 1992). The same hardware was used during Phase II, but upgrades were made for Phases III and IV. The number of measured channels increased from 185 in Phase II to 201 in Phase IV. Throughout Phase II testing, the inflow measurements and the non-rotating turbine measurements were acquired at slower sample rates than that of the rotating measurements. The slower rate channels were interpolated during post-processing to a common 520.83 Hz rate for all channels. During Phases III and IV, all of the channels were sampled at 520.83 Hz. Data were stored on 14-track magnetic tape during Phase II data acquisition, but technological advances in personal computing provided the capability for real time data collection and storage on optical disk during Phases III and IV. 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 14 which is taken from Butterfield et al. 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 14. 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 et al. 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 and the strain gages, but it is not feasible for a number of instruments because of the fact that 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 gages 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 gages. 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 about 2 months.

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 electronics 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 15. 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. Detailed measurement uncertainty estimates for Phase II data channels can be found in Butterfield et al. (1992) and Huyer et al. (1996). Error analysis and calibration procedures specific to wind turbine field testing are described in McNiff and Simms (1992).

Table 15. 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

The software described in Butterfield, et al. (1992) was used for Phase II data acquisition and processing, but new software was written for use in Phases III and IV. Faster PC's enabled the new viewing programs to convert PCM data to engineering unit data in real time and to display it on the monitor. A diagram of the signal path from PCM streams to useable data along with the possible viewing options is shown in Appendix B (p. B-59). 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 improvement was a program which 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 and Richardson number. Other parameters such as time, pitch angles, 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 as opposed to the difficult process used previously in Phase II. 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 flow charts presented in Appendix B, (pp. B-59 and B-60) illustrate the process of creating the engineering unit files which are stored on compact disc. Pressure calibrations were initiated with *psc.exe* that 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 gages 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, in conjunction 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. B-71. 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. B-72. 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 data base 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 data base provided a means of identifying baseline performance and dynamic stall occurrences. Additional post-processing software is described in Appendix B.

The Phase II data was originally processed in the manner described in Butterfield et al. (1992), but the convenience of studying all of the data in the same format required re-processing of the Phase II data. The engineering unit files stored on optical disk were converted back to counts and then processed with the *munch.exe* program to achieve consistent data format. This procedure is explained in Hand (1999).

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 reference pressure tube caused by rotation of the blade. This force was added to each measured pressure data value per Equations (1) and (2). Each of the probe pressures was also corrected in this manner.

$$P_{cor} = P_{meas} + P_{cent} \,, \tag{1}$$

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

$$\rho = 0.0034838 * \frac{P}{T} \quad \text{(Smithsonian Institution 1949);} \qquad (3)$$

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 = barometric 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. The pressure measured with the probes and corrected for centrifugal effects was one measure of dynamic pressure, and these channels are listed in Table 16. The dynamic pressure was also estimated from the stagnation point pressure at each of the full-chord pressure tap locations. 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 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. The stagnation point dynamic pressure (Q_{stag}) was used to normalize each of the blade surface pressures and is thus referred to as the normalization pressure (QNORM). Table 16 also includes these dynamic pressure measurements.

Table 16. 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
228 (II), 056 (III)	TP34	Total Pressure Probe at 34% Span	Pa
258 (II), 057 (III)	TP51, TP50	Total Pressure Probe at 51% Span	Pa*
033 (II), 156 (III)	TP67	Total Pressure Probe at 67% Span	Pa
155 (II)	TP86	Total Pressure Probe at 86% Span	Pa
157 (III)	TP83	Total Pressure Probe at 84% Span	Pa*
852 (III)	5HP1P	5-hole 91% Pressure	Pa
852 (IV)	5HP34P	5-hole 34% Pressure	Pa
855 (IV)	5HP51P	5-hole 51% Pressure	Pa
858 (IV)	5HP67P	5-hole 67% Pressure	Pa
861 (IV)	5HP84P	5-hole 84% Pressure	Pa
864 (IV)	5HP91P	5-hole 91% Pressure	Pa

* Phase III Channel ID indicates incorrect span locations of 50% and 83%

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 3. These values were recorded in the engineering unit files for each pressure tap.

$$C_p = \frac{P_{cor}}{Q_{stag}}; \tag{4}$$

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 and 95% span were both damaged so the tap at 92% chord on the lower surface was instrumented to provide an extrapolated value of the trailing edge tap. The intermediate tap pressure at 85% span, 36% chord 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). They 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 (5) and (6) 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.

$$C_N = \sum_{i=1}^{\#oftaps} \left(\frac{C_{p_i} + C_{p_{i+1}}}{2} \right) \left(x_{i+1} - x_i \right), \text{ and} \tag{5}$$

$$C_T = \sum_{i=1}^{\#oftaps} \left(\frac{C_{p_i} + C_{p_{i+1}}}{2} \right) \left(y_{i+1} - y_i \right); \tag{6}$$

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:

$$C_M = -\sum_{i=1}^{\#oftaps}\left[\left(\frac{C_{p_i}+C_{p_{i+1}}}{2}\right)\left[\left(x_{i+1}-x_i\right)\left(\frac{x_{i+1}-x_i}{2}+x_i-0.25\right)+\left(y_{i+1}-y_i\right)\left(\frac{y_{i+1}-y_i}{2}+y_i\right)\right]\right]. \quad (7)$$

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 in conjunction 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.

$$C_{Torque} = C_N \sin(\phi+\beta) + C_T \cos(\phi+\beta),$$
$$C_{Thrust} = C_N \cos(\phi+\beta) - C_T \sin(\phi+\beta),$$
$$C_L = C_N \cos(\alpha) + C_T \sin(\alpha), \text{ and}$$
$$C_{Dp} = -(C_N \sin(\alpha) - C_T \cos(\alpha)). \quad (8)$$

Torque and thrust coefficients were integrated along the span of the blade and multiplied by the number of blades to provide a rough estimate of the total aerodynamic thrust and torque applied to the entire rotor. All of the aerodynamic force coefficients are listed in Table 17 and illustrated in Figure 14. The estimated aerodynamic thrust and torque channel descriptions appeared in Table 11 for Phase II and Table 12 for Phases III and IV.

Table 17. Aerodynamic Force Coefficients

Channel	Channel ID	Description	Units
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*

* Phases III and IV only

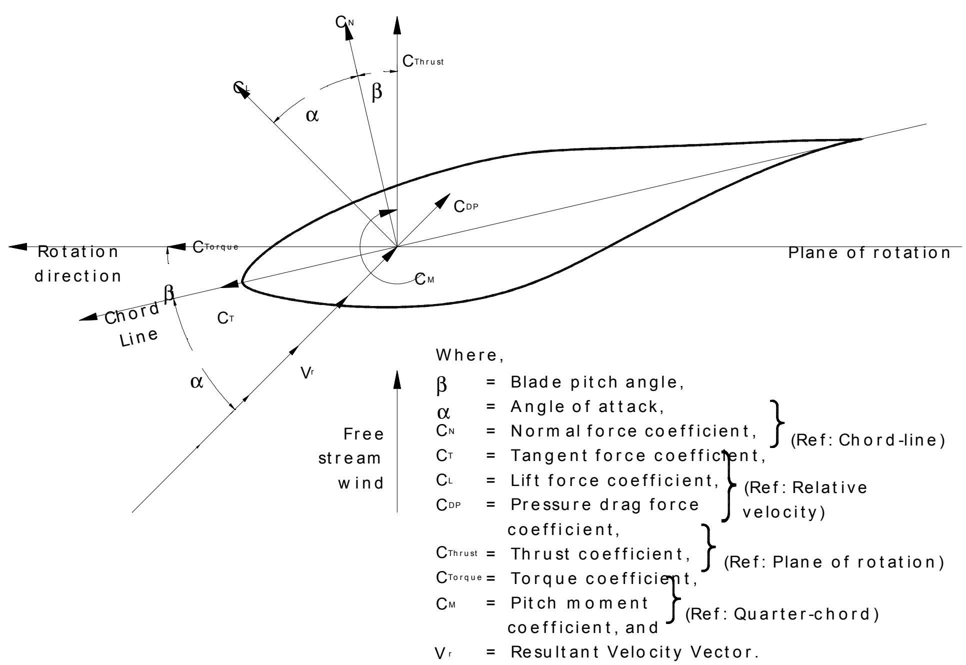


Figure 14. Aerodynamic force coefficient conventions.

Angle of Attack

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 et al. 1992). The upwash correction derived from a polynomial fit of the wind tunnel test data was applied to all of the local flow angle measurements, including those made with the 5-hole probes, to arrive at the angle of attack.

$$\alpha = -(5.427E-5)*\alpha_m^{\ 3} + (6.713E-3)*\alpha_m^{\ 2} + (0.617)*\alpha_m - 0.8293; \qquad (9)$$

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 calculated 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 for each phase of testing are listed in the tables below.

Table 18. Phase II and Phase III Upwash Corrected LFA Measurements

Channel	Channel ID	Description	Units
841 (II)	30AOA	AOA 30% Span - Upwash Corrected	deg
842 (II)	63AOA	AOA 63% Span - Upwash Corrected	deg
843 (II)	80AOA	AOA 80% Span - Upwash Corrected	deg
855 (III)	30AOA	AOA 30% Span - Upwash Corrected	deg
856 (III)	47AOA	AOA 47% Span - Upwash Corrected	deg
857 (III)	63AOA	AOA 63% Span - Upwash Corrected	deg
858 (III)	80AOA	AOA 80% Span - Upwash Corrected	deg
859 (III)	915HP	5HP 91% Span - Upwash Corrected	deg

Table 19. Phase IV 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°.

$$yawerr = wind\ direction - yaw \tag{10}$$

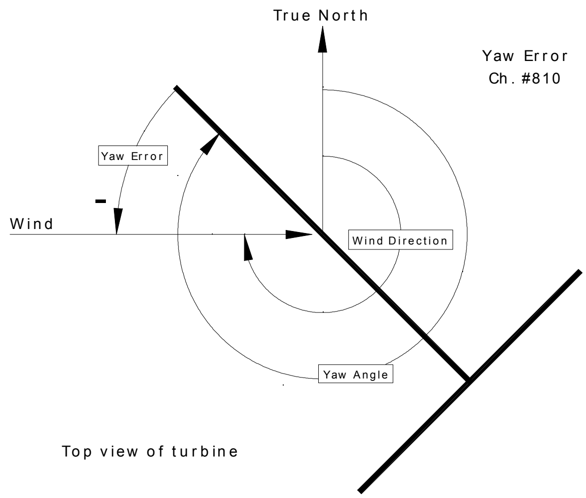


Figure 15. Yaw error angle convention.

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 units are converted from °/s to 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.

$$Ri = \frac{\left(\frac{9.8}{\Theta_m}\right)\left(\frac{\Delta\Theta}{\Delta Z}\right)}{\overline{V_{shear}}^2},\ \Theta = T\left(\frac{100{,}000}{P}\right)^{0.286},\ \overline{V}_{shear} = \frac{\sum_{n=1}^{N-1} \frac{WS_{n+1} - WS_n}{Z_{n+1} - Z_n}}{N-1}; \tag{11}$$

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.

Table 20. Miscellaneous Channels

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

* Phases III and IV only

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 either the Pitot probe or the 5-hole probe are actually dynamic pressure measurements. The stagnation pressure on the blade is also a measurement of dynamic pressure for the same reason. 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 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. These comparisons were made for Phase IV (1997) parked blade data and Phase IV (1997) rotating blade data resulting in different correction factors. The comparison was made for Phase II rotating blade data as well. Table 21 lists the correction factors for each phase of data for which they were calculated. Because the heaters added complexity by changing the box reference pressure during operation throughout Phase III and Phase IV (1996), corrections were not developed for these data.

Table 21. Reference Pressure Correction Factors

Phase	Correction factor
II rotating blade	-0.09
IV (1997) parked blade	0.28
IV (1997) rotating blade	0.30

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.

$$correction = factor * \frac{(Q_{stag\,30\%} - P_{cent\,30\%} + Q_{stag\,47\%} - P_{cent\,47\%})}{2}; \qquad (12)$$

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 depending on phase of data collection.

An example of the calculation of the correction magnitude for Phase IV (1997) 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.

$$correction = 0.3 * Q_{ave}$$

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

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

CONCLUSIONS

The instrumentation required to obtain data in the 3-D unsteady operating environment has evolved over the years. The original configuration used constant chord, untwisted blades with pressure measurements between 30% and 80% span. The twisted blade configuration added a full-chord pressure distribution at 95% span, and the local flow angle measurements were improved with the use of 5-hole pressure probes. Additional measurements provide inflow conditions, loads at the blade root and low-speed shaft, and position information. This report provides the reader with detailed information regarding the type of instrumentation used and the mathematical manipulations of the data.

Appendix A

Phase II, Phase III, and Phase IV Turbine Parameters

Basic Machine Parameters

- Number of Blades: 3
- Rotor diameter: 10.046 m (10.1 m for Phase II)
- Hub height: 17.03 m
- Type of rotor: fixed
- 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° (blade pitch angle was calibrated assuming 0° tilt)
- Cone angle: 3.417°
- Location of rotor: downwind
- Rotational direction: clockwise (viewed from downwind)
- Rotor overhang: 1.32 m (yaw-axis to center of rotation of rotor).

Rotor

Geometry

- Blade cross-section and planform:
  - Phase II: NREL design (Constant chord, no taper, no twist)
  - Phase III and IV: NREL S809 (Constant chord, no taper, optimally twisted)
- Root extension: 0.723 m
- Blade pitch angle (manually set by turbine operator):
  - Phase II: 12 degrees
  - Phase III: 3 degrees
  - Phase IV: -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:
  - Phase II: untwisted
  - Phase III and IV: see Table A.1.

Table A.1 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:
  - Phase II:
    - At 14.4% span: t = 43% chord (span refers to rotor center)
    - Between 14.4% and 30.0% span the thickness decreases linearly
    - At 30.0% span: t = 20.95% chord
    - Outboard of 30.0% span: t = 20.95% chord
  - Phase III and IV:
    - 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 A.2. 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 30% span (and outboard). In between the root and 30% 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. The twisted blade used in Phases III and IV is similar, except that the spar enlargement fits within the airfoil at 25% span. Figure A.1 illustrates the blade surface in the root region.

Table A.2. 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 et. al, 1992)

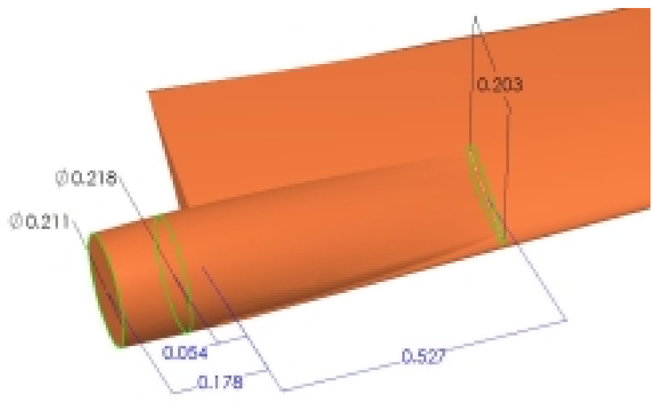


Figure A.1. Twisted blade root surface depiction (dimensions in meters).

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 A.3 (Butterfield et al. 1992; For additional wind tunnel measurements, see Somers 1997).

Table A.3. 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:
  - Phase II: 147.7 kg + 13 kg root mounted camera
  - Phase III: 215.1 kg
  - Phase IV (1996): 204 kg
  - Phase IV (1997): 206.5 kg.
- Hub mass:
  - Phase II: 269.1 kg (includes 3 instrumentation boxes, boom, camera)
  - Phase III: 236.3 kg (includes 3 instrumentation boxes
  - Phase IV (1996 and 1997): 288.3 kg (includes 3 instrumentation boxes, boom, camera) Figure A.2 depicts the hub-mounted instrumentation boxes, the boom and the camera that were implemented in Phase IV testing.

Figure A.2. Hub-mounted instrumentation boxes, boom, and camera.

- Blade material: Fiberglass/epoxy composite
- Blade mass (outside root):
  - Phase II:
    - Blade 1: 49.3 kg
    - Blade 2: 49.5 kg
    - Blade 3: 48.9 kg (not including root mounted camera. This caused a rotor imbalance).
  - Phase III: 71.7 kg (each blade, including root mounted camera. The cables that extend from the instrumented blade were wrapped around the root of the blade when the three blades were balanced. When the cables were routed to the hub upon installation, the blades masses were no longer balanced).
  - Phase IV (1996): 68 kg (each blade, including root mounted camera)
  - Phase IV (1997):
    - Blade 1: 68.8 kg
    - Blade 2: 68.8 kg
    - Blade 3: 68.9 kg (including root mounted camera).

- Blade center of gravity (from the root):
  - Phase II:
    - Blade 1: 1.63 m
    - Blade 2: 1.68 m
    - Blade 3: 1.61 m.
  - Phase III: 1.58 m (all blades)
  - Phase IV (1996): 1.53 m (all blades)
  - Phase IV (1997):
    - Blade 1: 1.51 m
    - Blade 2: 1.50 m
    - Blade 3: 1.50 m.
- Blade mass and stiffness distributions
  - Phase II: The root stiffness was measured by the strain gages, and the blade mass and stiffness distributions were estimated in Simms and Butterfield (1991) as shown in Table A.4. The root mounted camera (13 kg) was not included in the mass distribution.

Table A.4. Phase II, Untwisted Blade, Structural Properties.

Distance from Rotor Center (m)	Mass (kg/m)	Edgewise Stiffness (Nm^2)	Flapwise Stiffness (Nm^2)
5.030	5.59	37939	417556
4.527	5.59	37939	417556
4.024	6.57	49992	480118
3.521	7.29	61815	537514
3.019	8.02	73180	492614
2.516	8.75	84200	644844
2.013	9.72	95019	697074
1.510	12.14	115567	798091
1.007	17.00	406938	1169444
0.750	17.98	743278	998403
0.529	17.98	1369469	1439779
0.402		473517	473517

  - Phase III and IV: 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 A.5. Phase III and IV, Twisted Blade, Structural Properties.

Distance from Rotor Center (m)	Mass (kg/m)	Edgewise Stiffness (Nm^2)	Flapwise Stiffness (Nm^2)
5.029	9.32	46953	365070
4.526	9.25	46953	387600
4.023	10.22	65974	436440
3.520	11.19	84468	512420
3.018	12.06	105560	583420
2.515	12.95	123480	650900
2.012	13.49	149420	737010
1.509	16.92	232180	997640
1.006	46.09	710230	1332800
0.749	45.18	1302400	1556800
0.508	30.14	2320700	2322100
0.402		473517	473517

- First edgewise eigenfrequency:
  - Phase II: 8.75 Hz
  - Phase III and IV:
    - Non-instrumented blade: 8.16 Hz, 0.84% damping
    - Instrumented blade: 7.97 Hz, 0.69% damping.
- First flapwise eigenfrequency:
  - Phase II: 4.70 Hz
  - Phase III and IV:
    - 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

- Rotor inertia: 1356 kg m^2 w.r.t. low-speed shaft; includes boom and instrumentation boxes used in Phase IV configuration
- Inertia of rotating system (rotor, low-speed shaft, gearbox, high-speed shaft): 1535 kg m^2 w.r.t. low-speed shaft; includes boom and instrumentation boxes used in Phase IV configuration
- 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)
- Frequency of drive train: Not available
- Power train efficiency:
  - Gearbox: 97%
  - Windage, couplings, main shaft bearings: 98%
  - Generator: The efficiency curve (in %) of the combined system (gearbox + generator) versus generator power (kW) is a sixth order polynomial as follows:

    $$Eff = (-1.9717\cdot10^{-5})\cdot P_{gen}^{6} + (1.5989\cdot10^{-3})\cdot P_{gen}^{5} + (-5.1150\cdot10^{-2})\cdot P_{gen}^{4} + (8.2486\cdot10^{-1})\cdot P_{gen}^{3} + (-7.1329\cdot10^{0})\cdot P_{gen}^{2} + (3.2622\cdot10^{1})\cdot P_{gen} + (9.2674\cdot10^{0}).$$

    Thus, the efficiency is fairly constant at about 78%.
- The low-speed shaft torque measurement requires a correction due to calibration errors in the Phase II and Phase III data as follows:
  - Phase II: $T_{corr} = 1.08\cdot T_{measured}+15.16$
  - Phase III: $T_{corr} = 0.97\cdot T_{measured}-196.43$
- Maximum brake torque: 115.24 Nm
- The inertia of the low-speed shaft + gearbox + high-speed shaft may be found by subtracting the rotor inertia from that of the rotating system.
- The stiffness of the low-speed shaft, gearbox, and high-speed shaft as a lumped parameter is $1.70\cdot10^{5}$ Nm/rad.

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 4 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: 48118 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.

Full-System Modal Analysis

Table A.6: Phase II, Untwisted Blades, Including Instrumentation Boxes, Boom and Camera; Phase IV, Twisted Blades, Including Instrumentation Boxes, Boom and Camera; Blade 3 at 0°, Blade 1 at 120°, and Blade 2 at 240°.

Mode Shape Description	Phase II Frequency and Damping	Phase IV Frequency and Damping
Tower top bending, side-to-side		1.59 Hz 0.05%
Tower top bending, fore-aft Nacelle and rotor translating	1.7427 Hz 3.213%	1.72 Hz 0.75%
Nacelle yaw, blades move rigidly		2.22 Hz 5.74%
First out of plane blade bending, blades 1 & 2 symmetric, blade 3 out of phase, coupled with nacelle pitch and tower fore-aft	3.424 Hz 1.773%	3.69 Hz 1.78%
First out of plane blade bending, symmetric, nacelle translating	4.029 Hz 1.591%	5.02 Hz 2.57%
First out of plane blade bending, blades 1 & 2 asymmetric, blade 3 in torsion, nacelle yaw and tower torsion	2.495 Hz 2.962%	5.32 Hz 2.69%
First out of plane blade bending, symmetric. First in plane bending, blades 1 & 3 move toward each other, blade 2 low in-plane motion. Nacelle pitch	5.555 Hz 1.531%	5.77 Hz 4.13%
First out of plane blade bending, blades 1 & 2 symmetric, blade 3 out of phase. First in plane bending, blades 2 & 3 move towards each other, blade 1 low motion		6.43 Hz 4.77%
Tower bending side to side as if fixed on ends. First in plane blade bending, blades 1 & 2 move toward each other, blade 3 moves to the side toward which tower is bending	7.381 Hz 1.086%	7.87 Hz 1.14%
Tower bending fore-aft as if fixed on ends. Second out of plane blade bending, blades 1 & 2 symmetric, blade 3 out of phase. First in plane bending, blades 1 & 2 come together, blade 3 low in plane motion.	8.935 Hz 1.269%	8.68 Hz 1.33%
Second in plane blade bending, blades 1 & 2 towards each other. Blade 1 second out of plane bending. Boom up & down, nacelle pitch.	11.17 Hz 0.894%	
Second out of plane bending, blades 1 & 2 asymmetric, blade 3 in torsion		12.12 Hz 0.49%
Third out of plane bending, blades 1 & 3 symmetric, blade 2 out of phase. Boom side to side bending and nacelle yaw.	12.341 Hz 1.137%	
Nacelle pitch. Second out of plane bending, blades 1 & 2 symmetric, blade 3 out of phase. First in plane bending, blades 1 & 2 move toward each other, blade 3 low in plane motion.		13.33 Hz 1.00 %
Third out of plane bending, blade 1 & 2 symmetric, blade 3 out of phase. Boom up & down bending out of phase with nacelle pitch	14.172 Hz 0.973%	
Fourth flap blade bending, blades 1 & 2. Blade 3 in torsion, coupled with local flow angle flag devices' local modes.	17.394 Hz 0.847%	
Second tower side to side. Second out of plane bending, blades 1 & 2 symmetric, blade 3 out of phase		17.93 Hz 1.14%

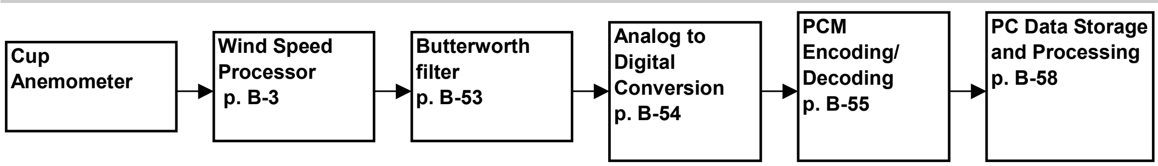
Appendix B

Instrumentation, Data Collection, and Data Processing for Phases III and IV

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)



Wind Speed Processor

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. B-69).

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 insure 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 2 months at most. On occasion, the processors were adjusted during a series of data collection.

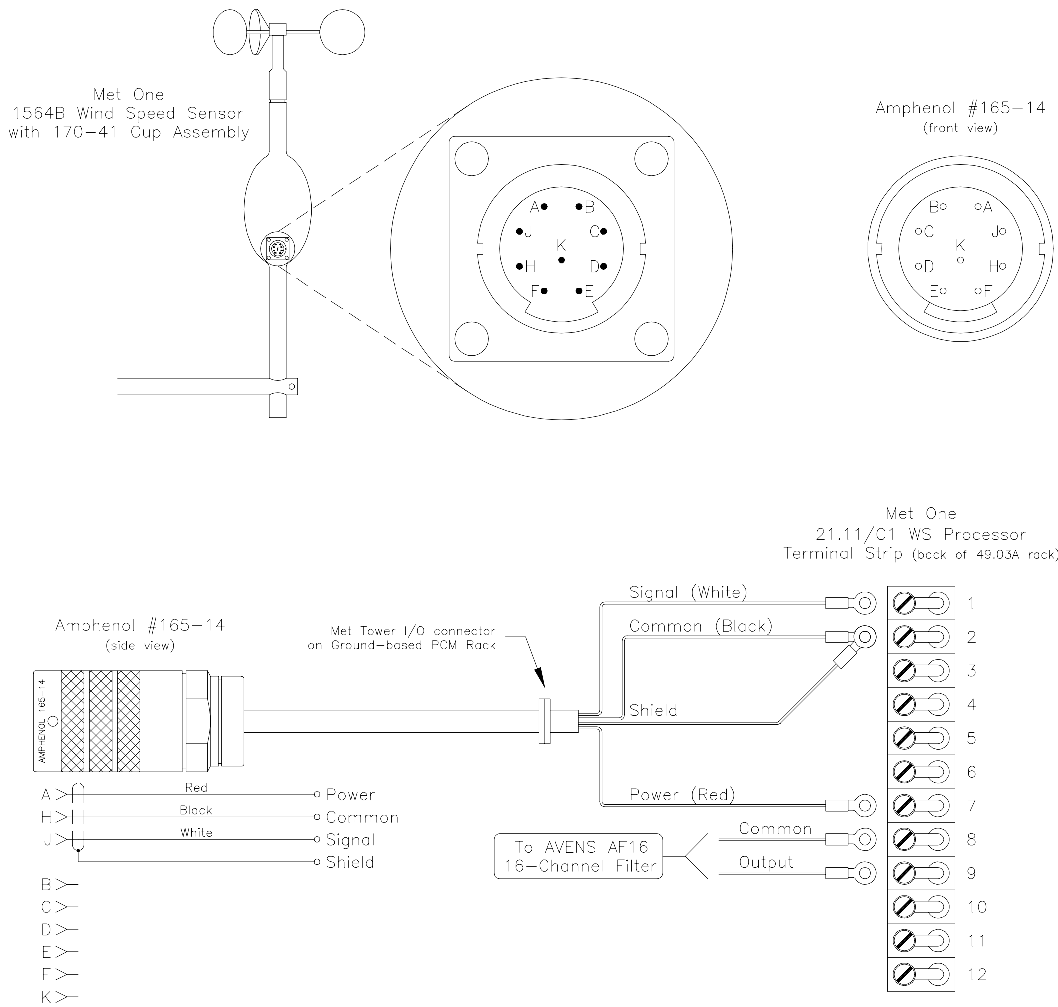
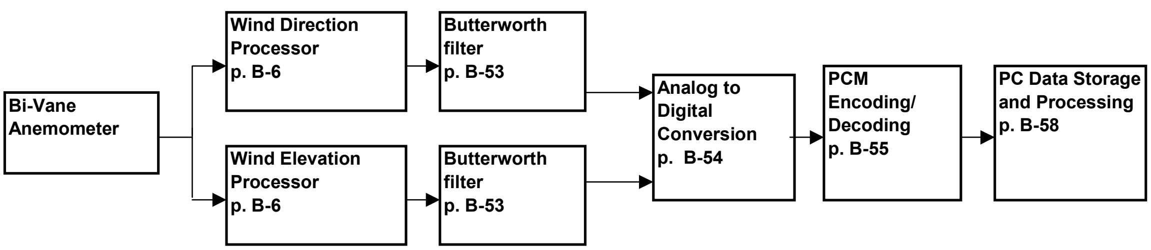


Figure B.1. Cup anemometer wiring diagram.

Anemometers (Bi-Vane)

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 insure 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 by the manufacturer prior to Phase III data collection. The north local met tower bi-vane was calibrated by the manufacturer prior to Phase IV data collection. Amplifier adjustment, offset determination, and electronics path calibrations were performed prior to each series of data collection which lasted less than 2 months.

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 insure 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 by the manufacturer prior to Phase III data collection. The North local met tower bi-vane was calibrated by the manufacturer prior to Phase IV data collection. Amplifier adjustment, offset determination, and electronics path calibrations were performed prior to each series of data collection which lasted less than 2 months.

Note: The processor calibration voltages were not updated after the manufacturer calibration performed prior to Phase IV. These voltages were updated prior to the second series of Phase IV during the spring of 1997.

Phase III (1995) and Phase IV (1996)
S/N 055 Sensitivity = 12.75 Hz/deg, ELO = 0.539V, EHI = 4.461V (south met tower)
S/N 056 Sensitivity = 12.20 Hz/deg, ELO = 0.451V, EHI = 4.549V (north met tower)

Second season of Phase IV (1997)
S/N 056 Sensitivity = 12.24 Hz/deg, ELO = 0.458V, EHI = 4.542V (north met tower)

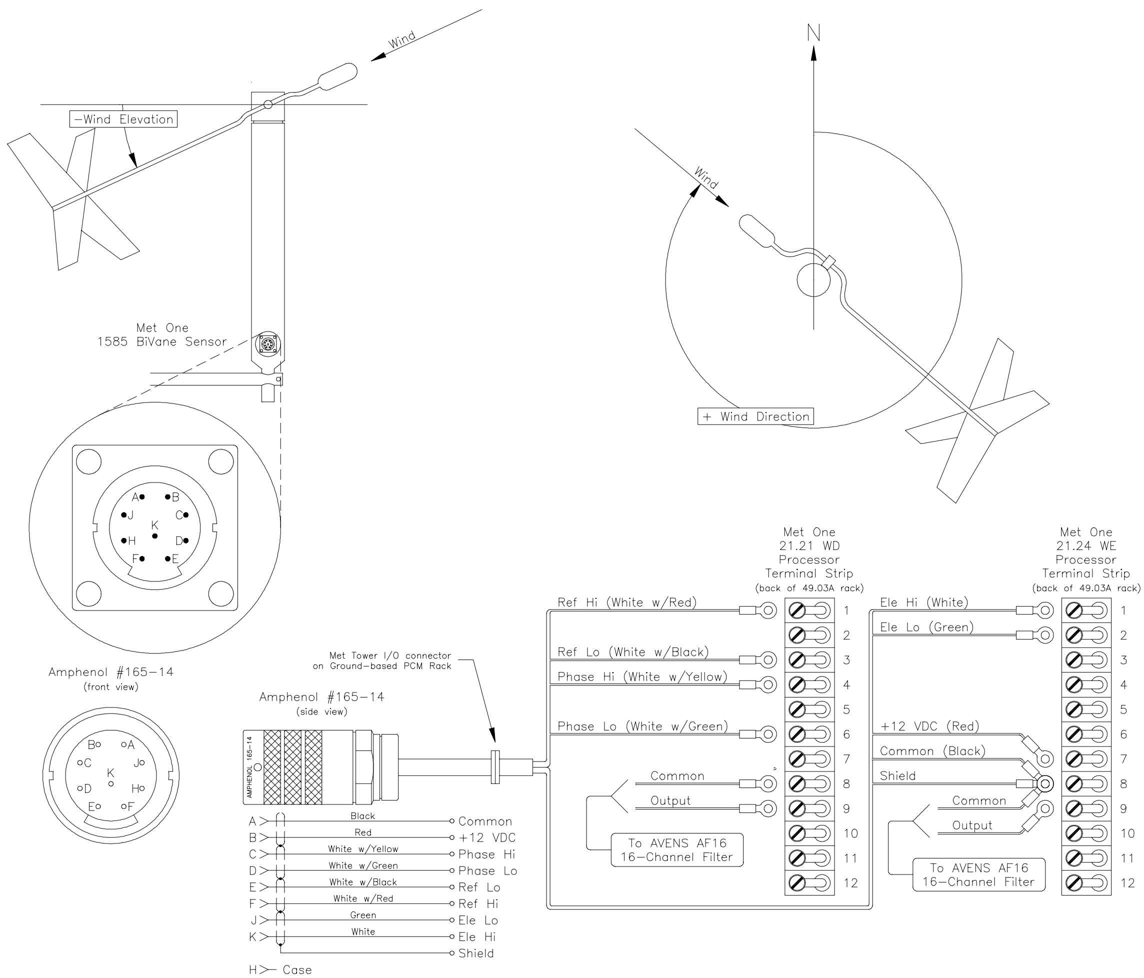
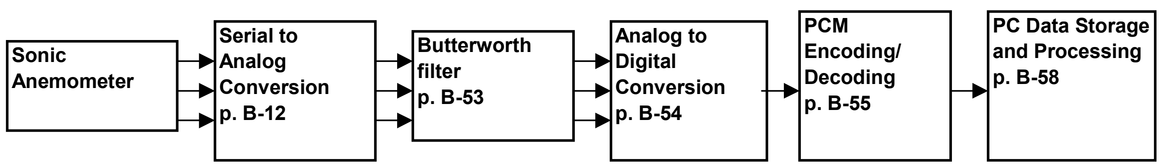


Figure B.2. Bi-vane anemometer wiring diagram.

Anemometers (Sonic)

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 insure 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 2 months.

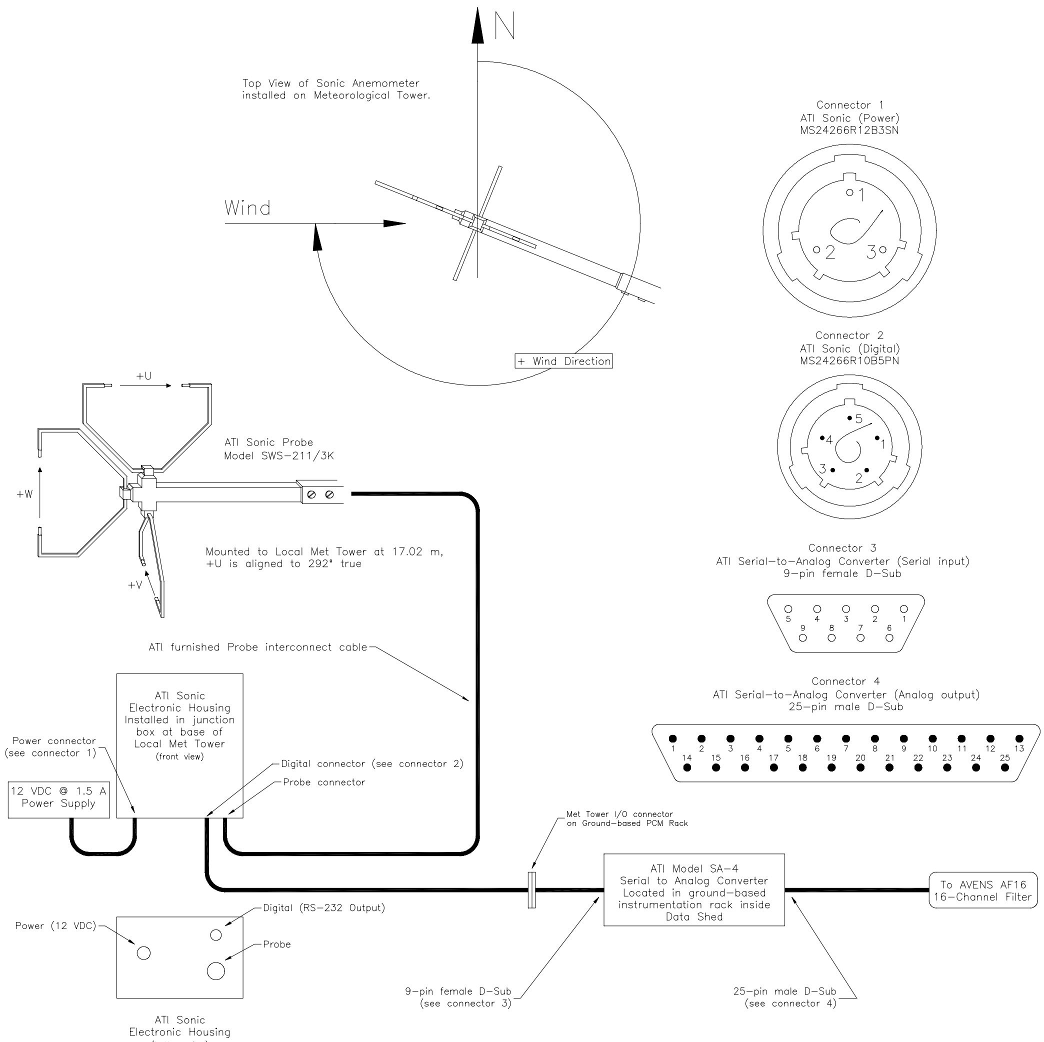
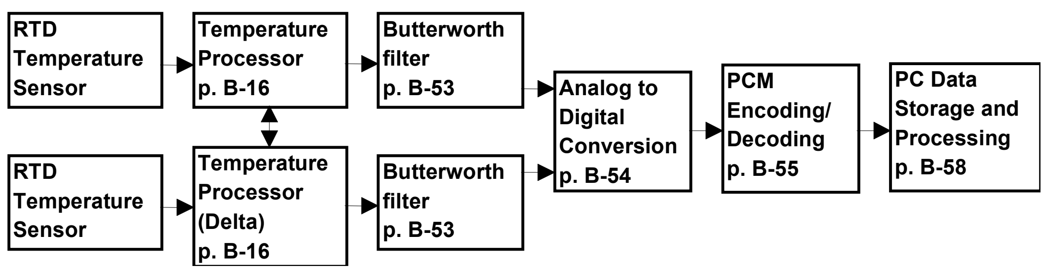


Figure B.3. Sonic anemometer wiring diagram.

Temperature (Ambient)

Channel	ID Code	Description
320	LMT2M	Local met temperature 2.4 m
322	LMT24M	Local met temperature 24.48 m (data1-data7)
322	LMDT	Local met Δ temperature, 24.48 m - 2.4 m (data8-Phase IV)

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)

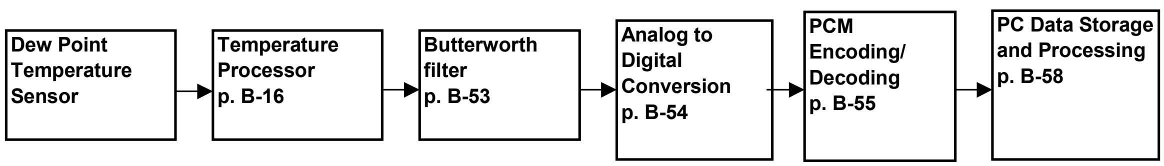


Note: Sensor is mounted in an aspirated radiation shield. If the aspirating fan malfunctions, a light on the met rack is illuminated, an audible alarm sounds, and data collection is halted.

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	LMT24M	Local met temperature 24.48 m (data1-data7)
322	LMDT	Local met Δ temperature, 24.48 m - 2.4 m (data8-Phase IV)
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 Phase III and Phase IV 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

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 insure 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 III data collection. Amplifier adjustment, offset determination, and electronics path calibrations were performed prior to each series of data collection which lasted less than 2 months.

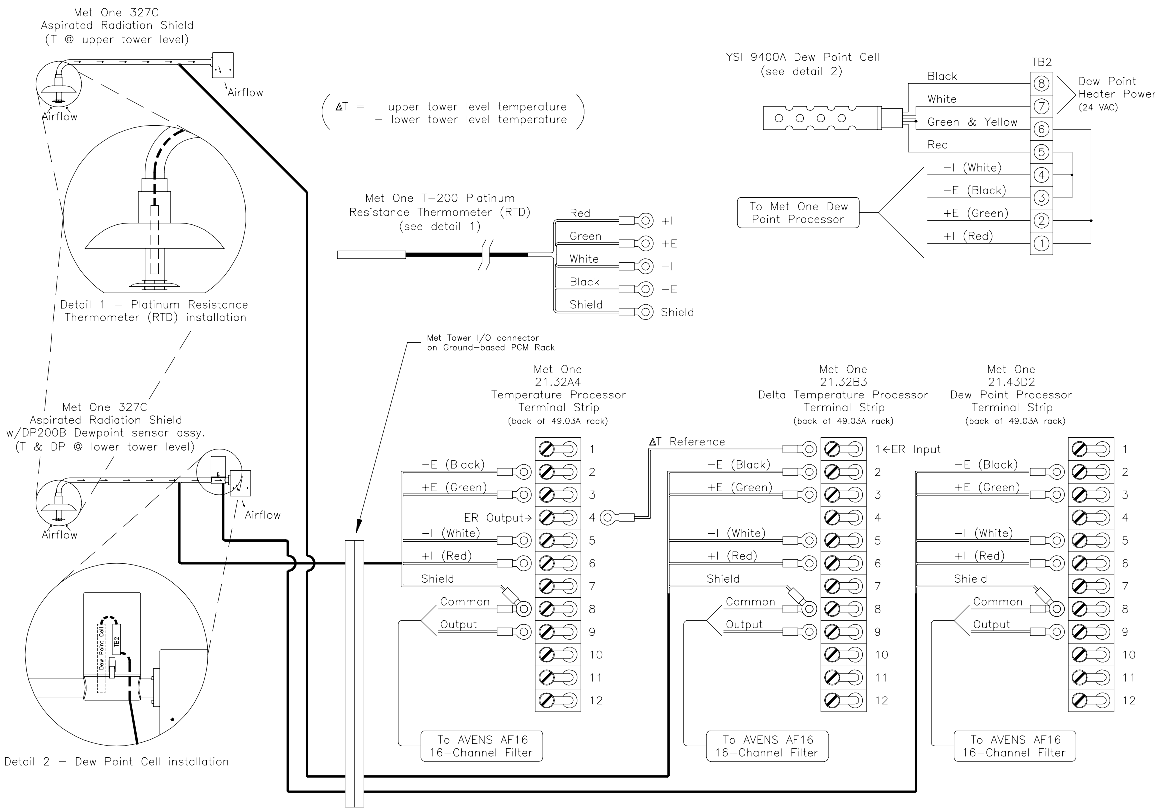
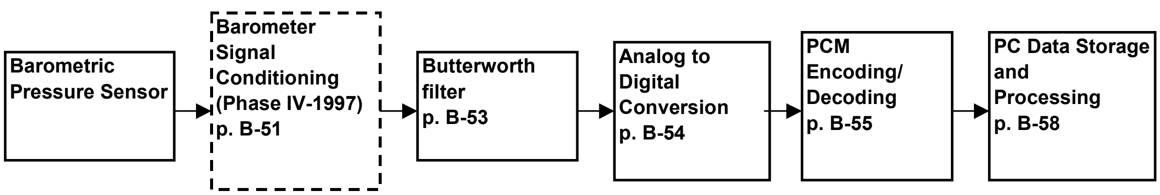


Figure B.4. Temperature, delta temperature, and dew point wiring diagram.

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



Note: The barometer that was used for Phase III data sets data1-data6, parked1, parked2, slwrot2, and slwrot3 was calibrated with a maximum value of 80,000 Pa. Thus, the instrument's maximum input was exceeded during these data campaigns.

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 insure 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 each phase of data collection. The electronic path calibration was performed prior to each series of data collection which lasted less than 2 months.

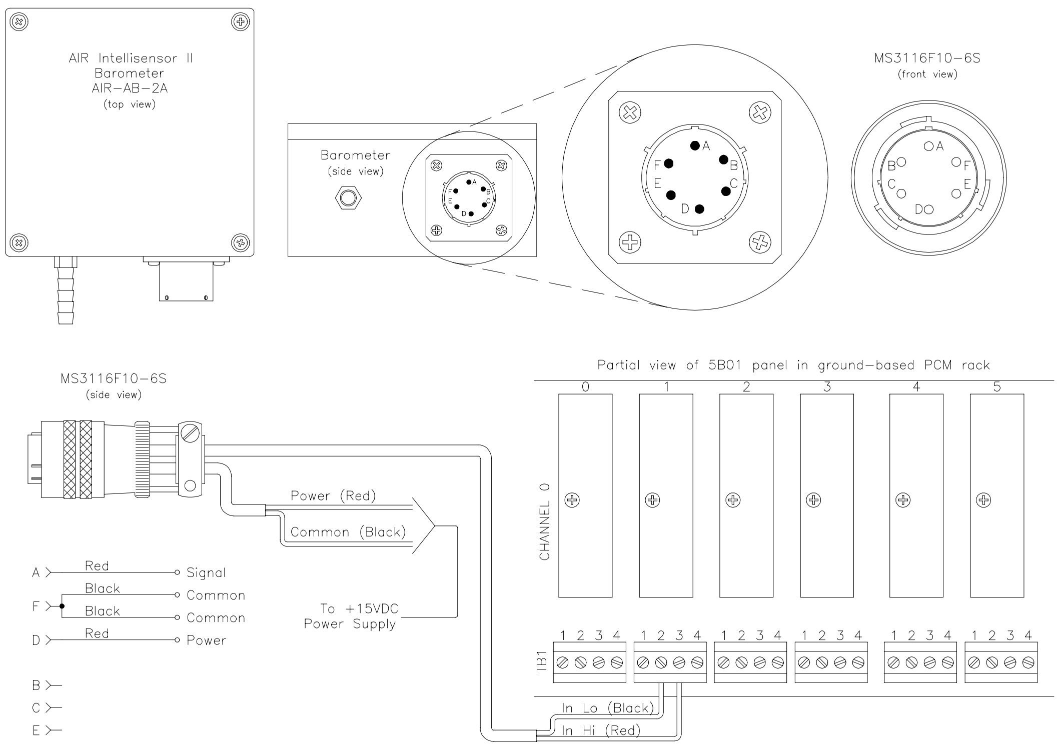
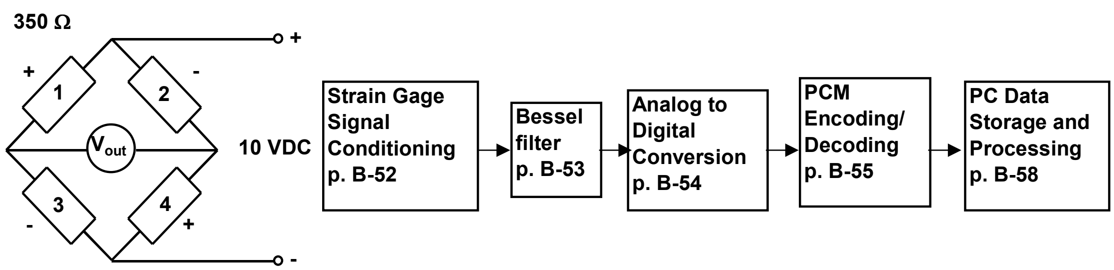


Figure B.5. Barometer wiring diagram.

Channel	ID Code	Description
225	B1RFB	Blade 1 root flap bending moment
227	B1REB	Blade 1 root edge bending moment
229	B2RFB	Blade 2 root flap bending moment
231	B2REB	Blade 2 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	± 5000με
Resolution	2000 με / 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:
1. Flap bending is positive in downwind direction; Edge bending is positive opposite the direction of rotation.
2. The blade 1 flap and edge bending gages are wired backwards so the slopes have opposite signs of those of the other blades. However, the measurement is in the same orientation for all three blades.
3. The gage specifications listed above correspond to the gages used during Phase IV. The gages used during Phase III were similar, but they were glued to the shaft rather than welded.

Calibration Procedures

Application of known loads - (A1)

A custom jig was used for strain gage 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 producing new slope values.

Determination of the offset was done differently between Phases III and IV. Essentially, the root flap and edge offsets were determined by placing each blade in a position where the respective load is zero. The offsets for the low-speed shaft gages were 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.bat* process, and the values are placed in the *master.hdr* file.

Slope coefficient calibration:

1. The man-lift person notifies ground people 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 (number of variables), and the PCM stream on which the channels are contained is selected in *gencal.cap*. All of the strain gages are on PCM stream 2 except the yaw moment strain gages (NAYM) which are on PCM stream 3. During Phase III, the blade strain gages were included with the blade 3 root gages. The low-speed shaft X-X bending channel (LSSXXB) is included with the blade 3 flap bending channel (B3RFB). It is assumed that the low-speed shaft Y-Y bending channel (LSSYYB) has the same slope as bending about the X-X axis. The yaw moment channel (NAYM) is calibrated separately because it is on a different PCM stream than the other strain gages. The low speed shaft torque channel (LSSTQ) is included with each of the three edge bending channels (B1REB, B2REB, B3REB).
2. The *gencal.exe* program is run while the weights are applied from 0 to 100 lb in 20 lb increments with 3 repetitions at each level. *Gencal.exe* 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 three blades to calibrate blade strain gages, low speed shaft X-X bending gages, low speed shaft torque, and yaw moment strain gages. For Phase IV calibrations the blades were loaded in both positive and negative bending conditions.
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 (lb), R = blade radius (5.023 m), and r = radial distance to strain gage (17 in). Plot each curve in Excel, and perform a linear curve fit to determine the slope. Enter the slope values in the temporary header file, *strains.hdr*.

Offset coefficient calibration (Phase III):

1. The man-lift person positions each blade at 90° azimuth angle, and the computer person selects the corresponding root flap bending channel (B1RFB, B2RFB, B3RFB) in the *gencal.exe* input file.

2. The *gencal.exe* program is run with the operator collecting samples. At this location of the rotational cycle, the blade should not be loaded in the flap bending direction (0 Nm) so the count value is used as a single point in determining the offset.
3. The same process is repeated for the root edge bending gages, but each blade is positioned at 180° which corresponds to 0 Nm edge bending moment.
4. Releasing the rotor brake removed any low-speed shaft torque load. The offset was determined by sampling the low-speed shaft torque (LSSTQ) channel. Assuming that the torque measurement is not dependent on the azimuthal position, this method would provide a reasonable offset. This assumption was later determined to be invalid, and a torque correction was created using Phase IV data (Tcorrected = 0.97*Tmeasured - 196.43). This calibration was improved for Phase IV by accounting for the cyclic nature of the torque channel.
5. In order to determine the offset for the low-speed shaft bending channels, the turbine was powered to 72 rpm. The power was shut off, and the rotor slowed to a stop. While the rotor was slowing, the low-speed shaft X-X and Y-Y bending channels (LSSXXB, LSSYYB) were recorded. The average provided the offset at zero load.

Offset coefficient calibration (Phase IV)

1. All of the strain gages, except yaw moment, were listed in a **.cao* file for input to *gencal.exe*. The instrumented blade was positioned at 30° increments over one complete rotational cycle. Three samples were obtained at each position.
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 along with the low speed shaft torque averaged 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 entered in *strains.hdr*.

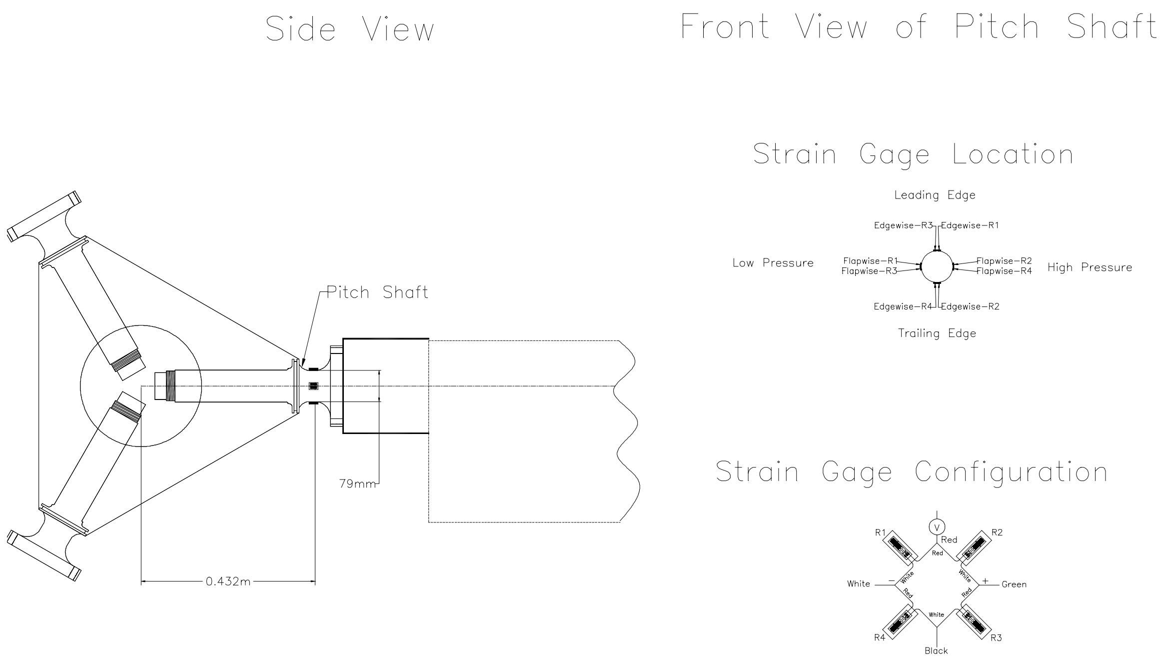
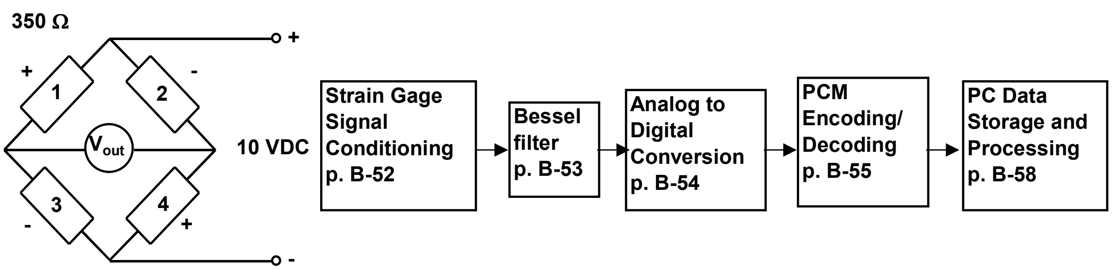


Figure B.6. Root bending strain gage configuration.

Channel	ID Code	Description
215	B325FB	Blade 3 25% flap bending moment (Phase III)
217	B325EB	Blade 3 25% edge bending moment (Phase III)
219	B360FB	Blade 3 60% flap bending moment (Phase III)
221	B360EB	Blade 3 60% edge bending moment (Phase III)

Location	Blade 3, 25% span and 60% span
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.



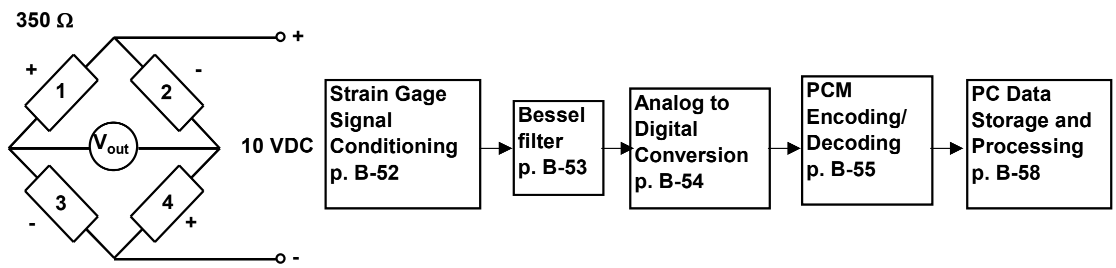
Note:
1. Flap bending is positive in downwind direction; Edge bending is positive in direction of rotation.
2. These strain gages were applied with epoxy within the skin of the blade during manufacturing.

Calibration Procedures (See p. B-21)

Strain Gages (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)



Calibration Procedures (See p. B-21)

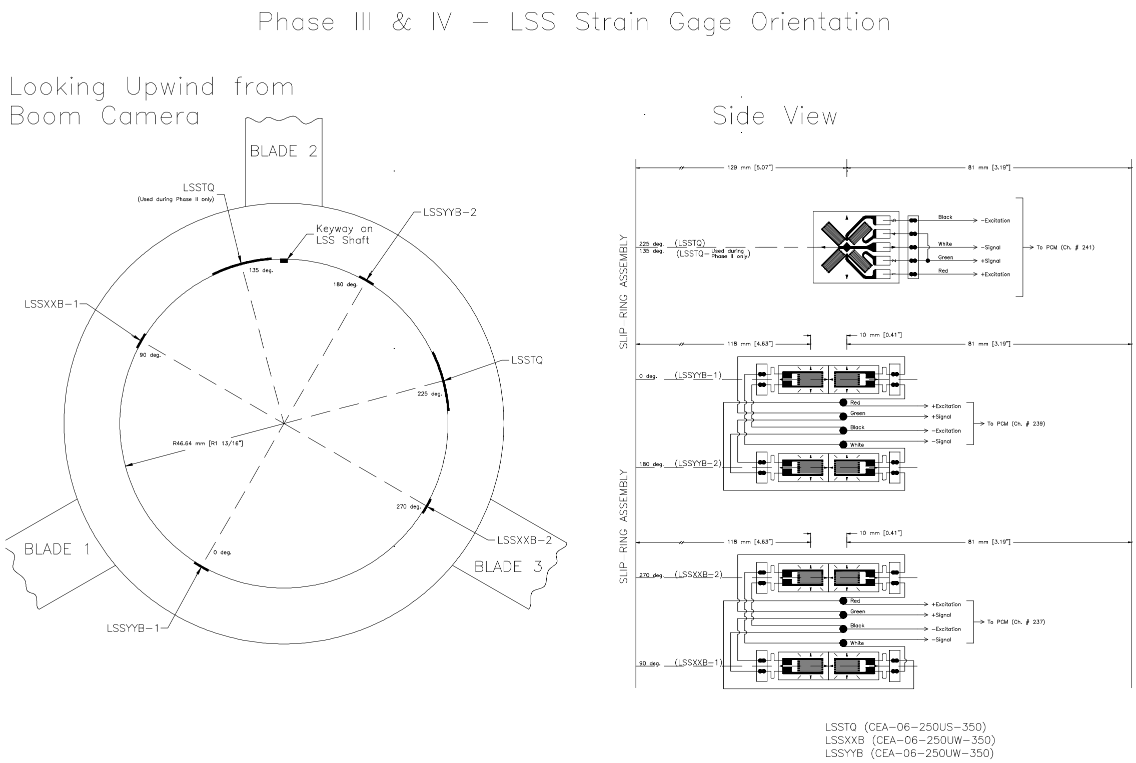


Figure B.7. Low-speed shaft strain gage configuration.

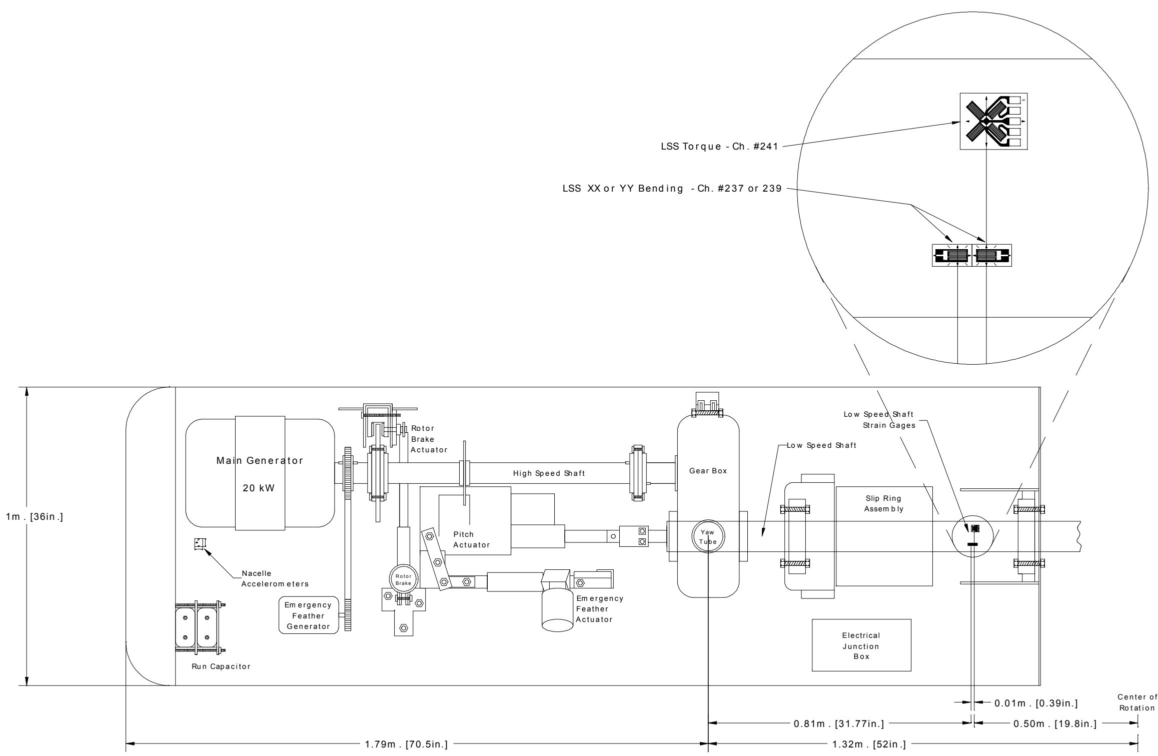
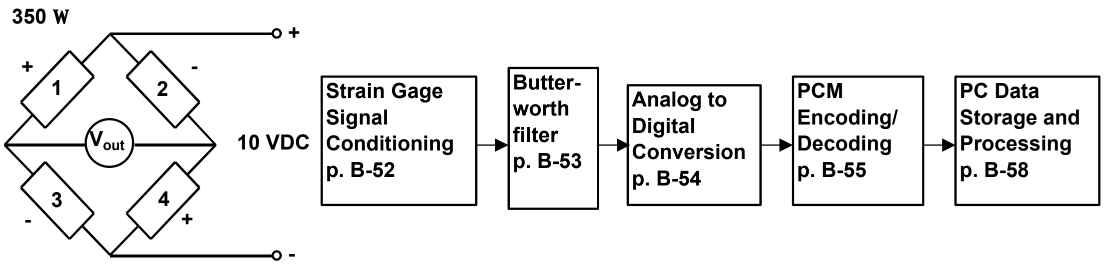


Figure B.8. Low-speed shaft strain gage location within nacelle.

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:



Calibration Procedures (See p. B-21)

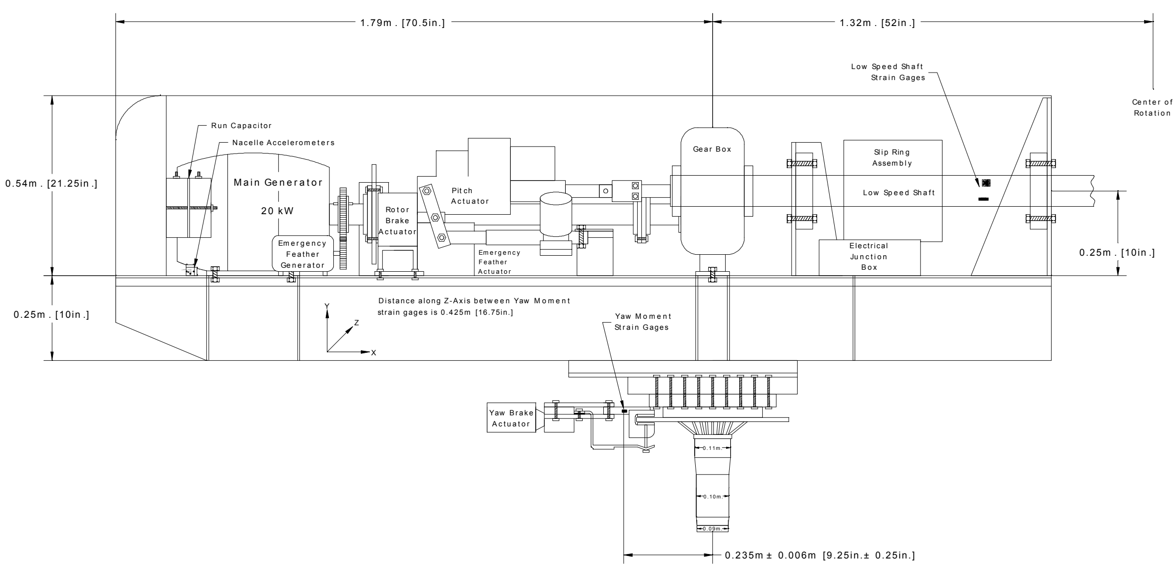
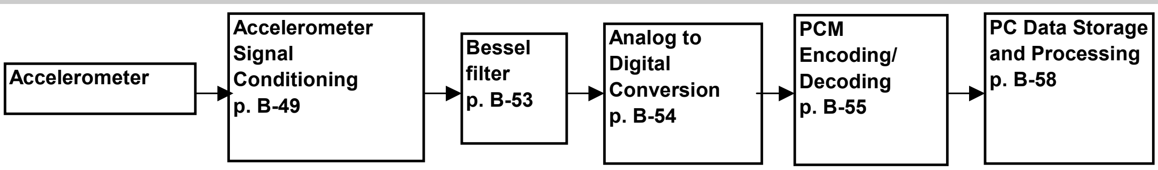


Figure B.9. Yaw moment strain gage configuration.

Accelerometers

Channel	ID Code	Description
201	B1ACFL	Blade 1 tip accelerometer – flap
203	B1ACED	Blade 1 tip accelerometer – edge
205	B2ACFL	Blade 2 tip accelerometer – flap
207	B2ACED	Blade 2 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	±10 g = ±2 V
Sensitivity	200 mV / g
Calibration method	Manufacturer specifications (M8) and electronics 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 (number of variables) in the first line to the number of channels to be calibrated, and insure 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.bat* batch file which invokes both *gencal.exe* and *genfit.exe*. 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.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 accelerometers were calibrated upon replacement of damaged accelerometers. An electronic path calibration was performed prior to each series of data collection which lasted less than 2 months.

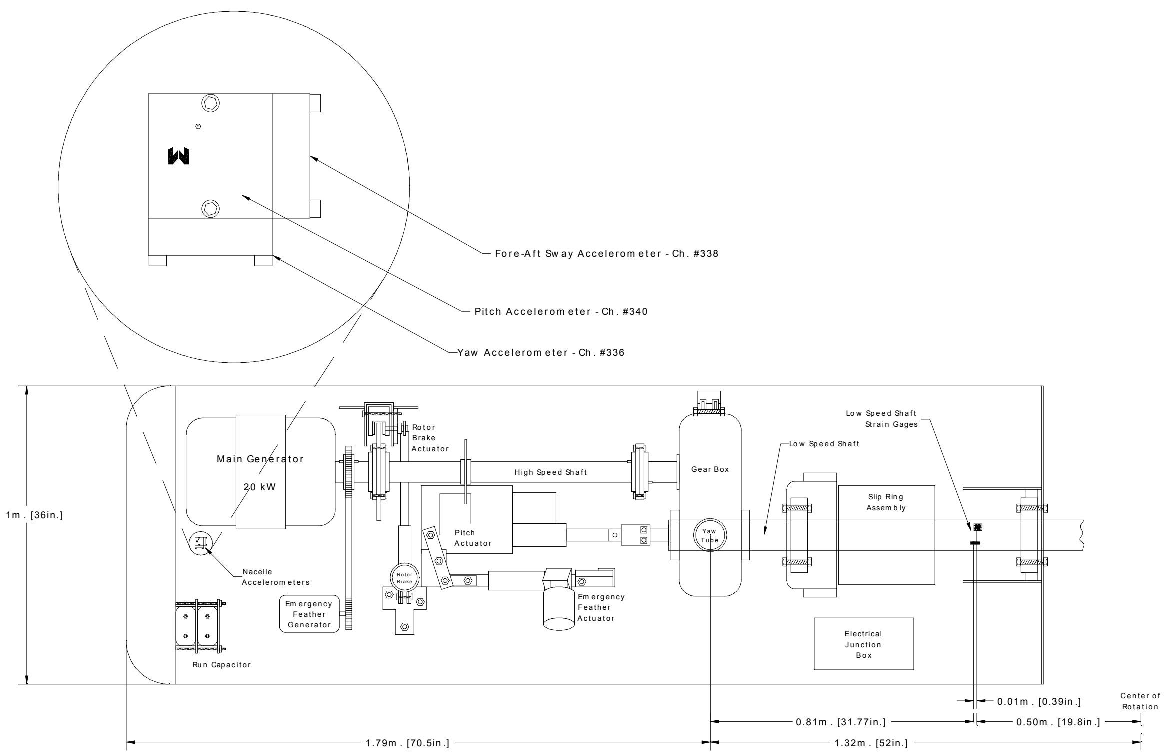


Figure B.10. Nacelle accelerometer configuration.

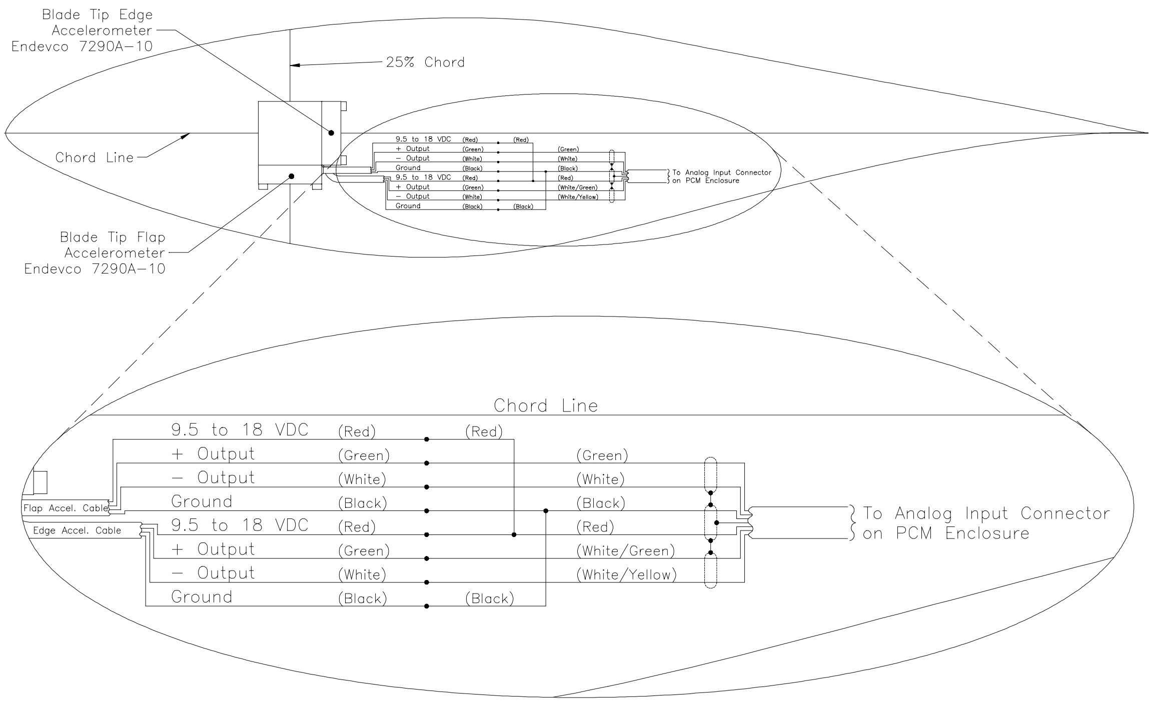
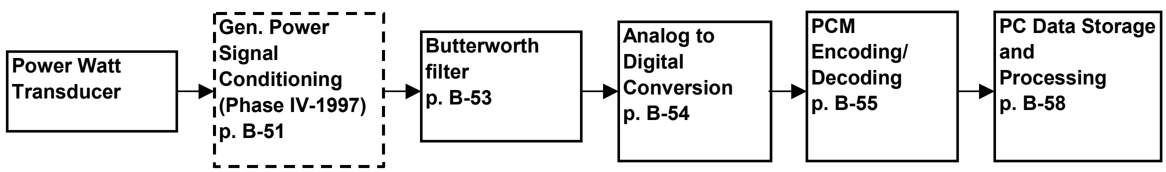


Figure B.11. Blade tip accelerometer configuration.

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 = -5V to 5V
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)

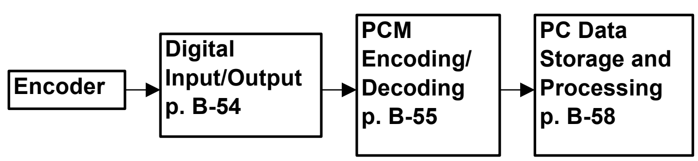
1. Modify *vbl.lst* so that the power channel is listed at the top of the file. Set NV (number of variables) in the first line to the number of channels to be calibrated, and insure that the correct PCM stream is specified in *gencal.cap* (PCM stream 3).
2. Connect the precision voltage generator to 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 Phase III and Phase IV. The electronic path calibration was performed prior to each series of data collection which lasted less than 2 months.

Channel	ID Code	Description
253	B1PITCH	Blade 1 pitch angle
255	B2PITCH	Blade 2 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



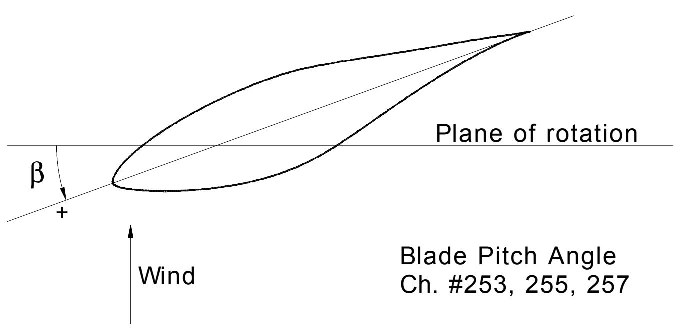


Figure B.12. Blade pitch angle orientation.

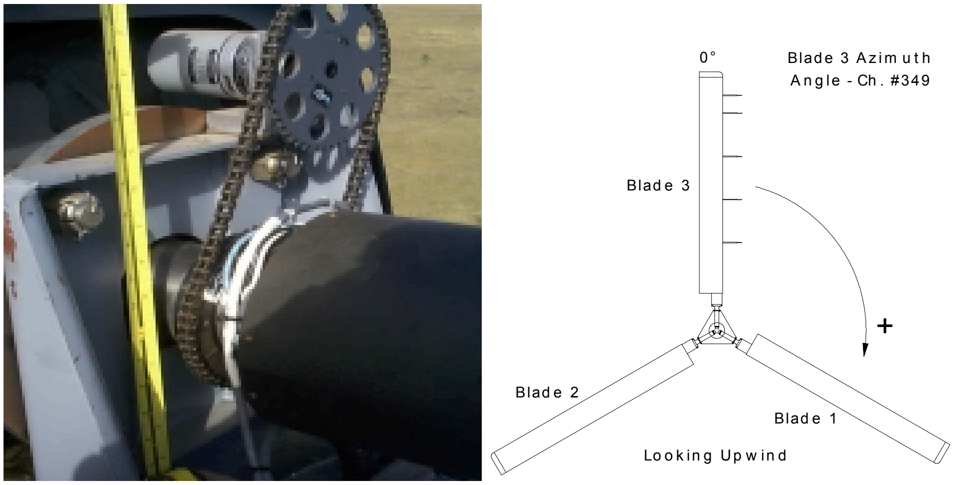


Figure B.13. Azimuth angle encoder photograph and orientation.

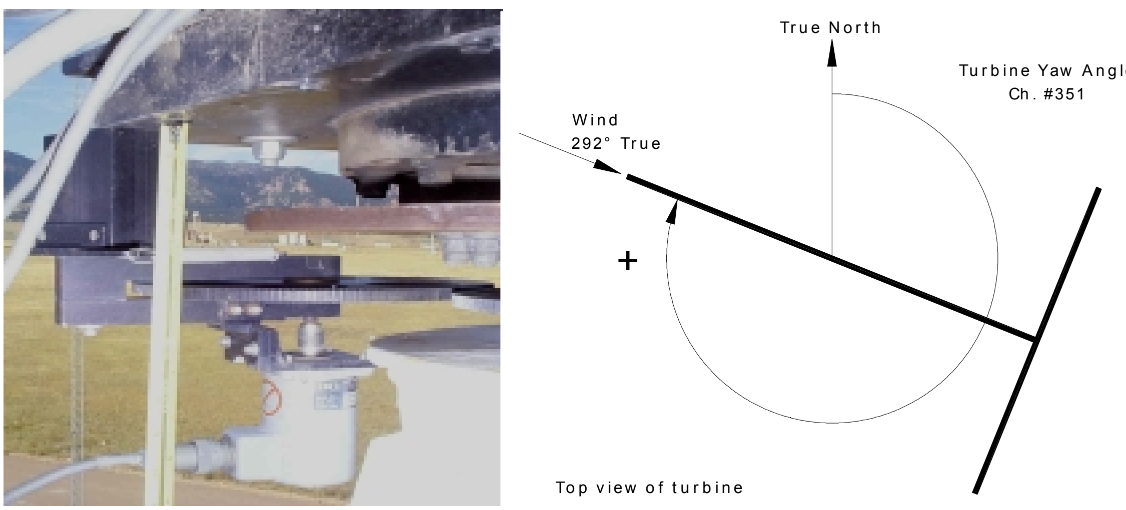


Figure B.14. Yaw angle encoder photograph and orientation.

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.

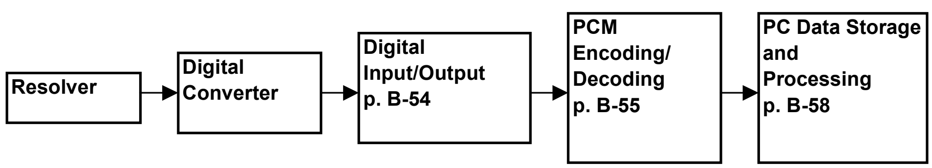
Calibration frequency

All encoders were calibrated by the manufacturer prior to Phase III data collection. The blade pitch offsets were determined prior to each series of data collection. The turbine yaw and azimuth angle offsets were determined prior to each series of data collection.

Digital Position Encoders (LFA Flags)

Channel	ID Code	Description
243	30LFA	30% span local flow angle (flag) Phase III only
245	47LFA	47% span local flow angle (flag) Phase III only
247	63LFA	63% span local flow angle (flag) Phase III only
249	80LFA	80% span local flow angle (flag) Phase III only

Location	LFA flag assembly at each primary span location on blade 3
Measurement type and units	local flow angle, degrees
Power Requirement	±15 V, 5V
Range	360° = 4096 counts
Resolution	0.08789 °/count
Calibration method	Manufacturer specifications (M10) and single point offset determination (S4)
Sensor description	Brushless resolver (size 11) 12 bit binary output PC card mount decoder Computer Conversions Corporation Model: TDS12-F-1PC, TDS36-F-1PC



Calibration Procedure

Manufacturer specifications - (M10)

1. A calibration was performed by Computer Conversions Corporation before installation of all resolvers.
2. Enter the slope (0.08789°/count) in the appropriate columns of *calconst.xls*.

Single point offset determination - (S4) - (This is a two-person operation requiring one person in the man-lift to position the flags and one person on the ground to operate the computer.)

1. Man-lift person notifies ground person which flag is to be calibrated. A custom test jig, built for the purpose of calibrating the flag transducers, is affixed to the mount holding the flag at 0°.
2. The ground person records the count value in the appropriate column of *calconst.xls*.

Calibration frequency

The encoders were calibrated by the manufacturer and the offsets determined prior to Phase III data collection. Note: the flags were replaced by 5-hole probes during Phase IV.

Local Flow Angle Flag (Phase III)

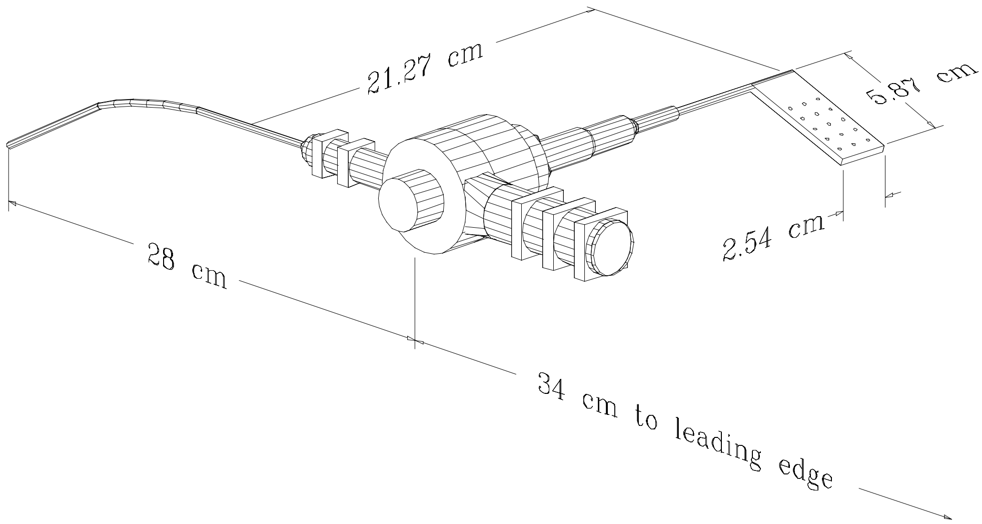
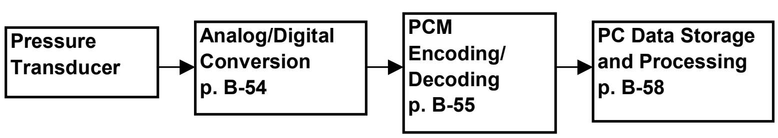


Figure B.15. Local flow angle flag assembly.

Pressure Transducers (30% and 47% span)

Channel	ID Code	Description
000-050 (even)	Ptt30ccc Ptt36ccc Ptt41ccc	Surface pressures at 30%, 36%, and 41% span tt = transducer tap number ccc = % chord pressure tap location
001-051 (odd)	Ptt47ccc Ptt52ccc Ptt58ccc	Surface pressures at 47%, 52%, and 58% span tt = transducer tap number ccc = % chord pressure tap location
056, 057	TP34, TP50	Total pressure probes at 34% and 51% span (Phase III) ** The header files incorrectly list a probe at 50% span.
052-060 (even)	5Hx34	5-hole probe at 34% span (Phase IV) x = designation of hole in 5-hole probe
053-061 (odd)	5Hx51	5-hole probe at 51% span (Phase IV) 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 40 Hz, and the measured pressure data showed no appreciable information above 40 Hz (Butterfield et al. 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. During Phase III a ramp from -0.8 to 0.8 psi in increments of 0.2 psi was used. During Phase IV (1996) a ramp from -0.9 to 0.9 psi in increments of 0.2 psi was used. During Phase IV (1997) the 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.

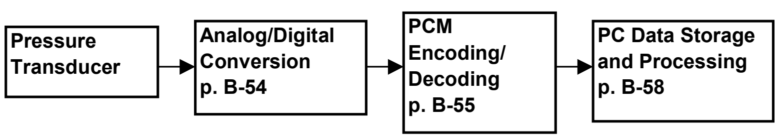
Pressure Tap Chord Locations

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 (even)	Ptt63ccc Ptt69ccc Ptt74ccc	Surface pressures at 63%, 69%, and 74% span tt = transducer tap number ccc = % chord pressure tap location
156	TP67	Total pressure probe at 67% span (Phase III)
152-160 (even)	5Hx67	5-hole probe at 67% span (Phase IV) 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

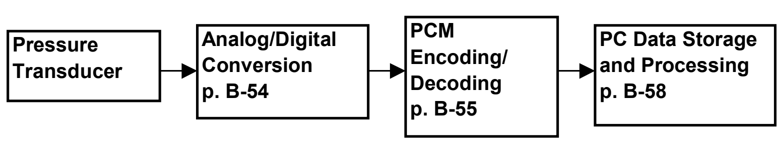


Calibration Procedure (See p. B-39)

Pressure Transducers (80% and 95% span)

Channel	ID Code	Description
101-145 (odd)	Ptt80ccc Ptt85ccc Ptt90ccc	Surface pressures at 80%, 85%, and 90% span tt = transducer tap number ccc = % chord pressure tap location
157	TP83	Total pressure probe at 84% span (Phase III) ** The header files incorrectly list this channel at 83% span.
153-161 (odd)	5Hx84	5-hole probe at 84% span (Phase IV) x = designation of hole in 5-hole probe
200-250 (even)	Ptt95ccc Ptt92ccc Ptt98ccc	Surface pressures at 95%, 92%, and 98% span tt = transducer tap number ccc = % chord pressure tap location
252-260 (even)	5Hx91	5-hole probe at 91% span

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
Resolution	2068 Pa / V
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. B-39)

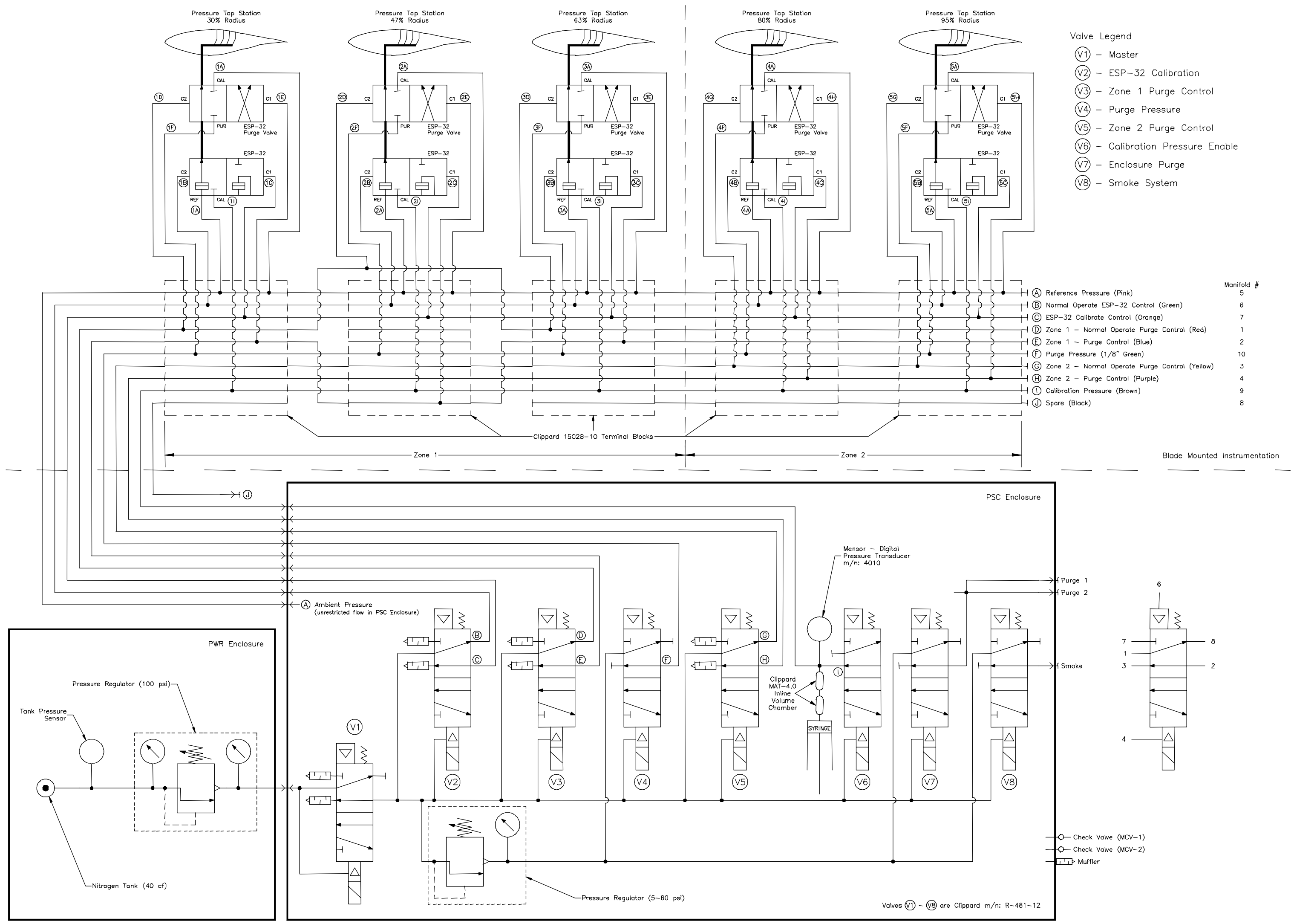
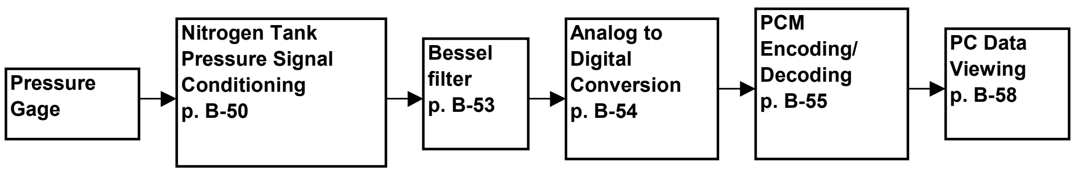


Figure B.16. Pneumatic layout.

Nitrogen Tank Pressure

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 2,000 psig
Resolution	
Calibration method	
Sensor description	



Calibration frequency

The pressure gage 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.

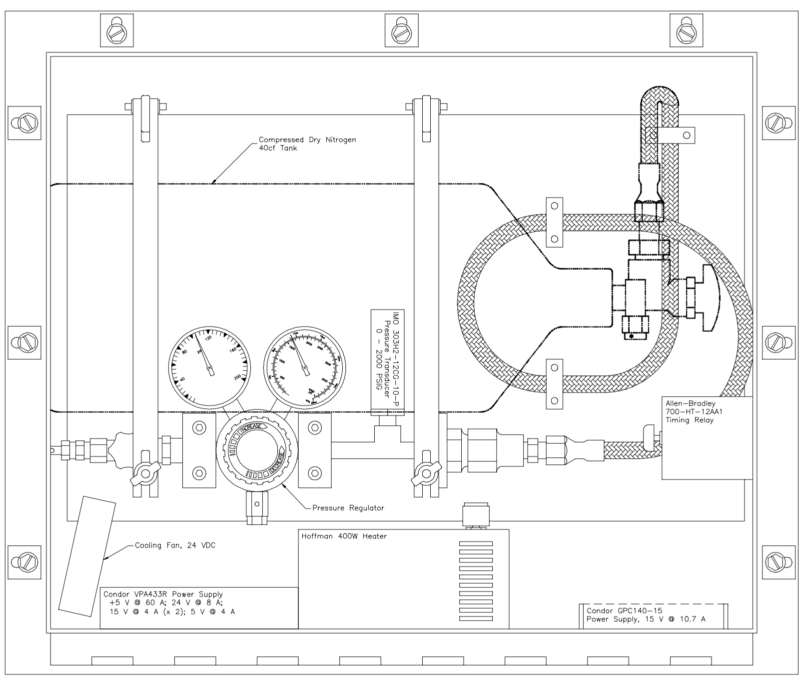
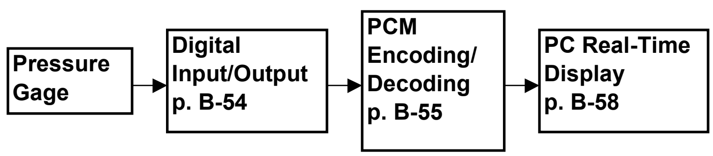


Figure B.17. Nitrogen tank enclosure.

Digital Differential Reference Pressure

Channel	ID Code	Description
259	N/A	Digital first 12 bits from Δ pressure
261	N/A	Digital last 12 bits from Δ pressure

Location	Rotor package
Measurement type and units	Calibration reference 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.
   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 2 months. The zero offset was usually determined each day of data collection.

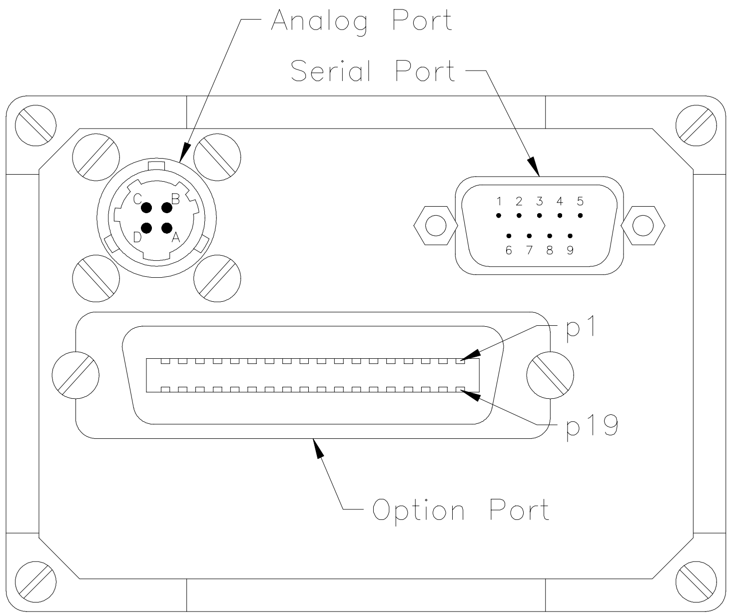
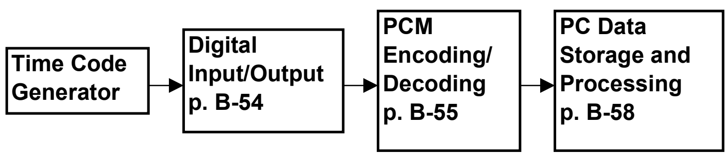


Figure B.18. Mensor electrical ports.

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: ±5ppm 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.

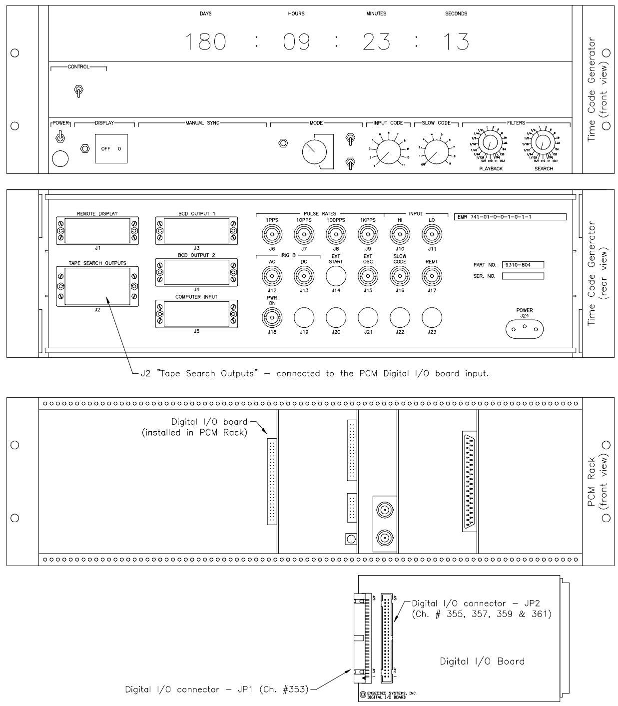


Figure B.19. Time code generator.

Accelerometer Signal Conditioning

Channel	Description
201-211 (odd), 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 wideband 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 wideband 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 (Phase IV(1997))
334	Barometric pressure (Phase IV(1997))

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

Note: The barometric pressure and generator power channels were not signal conditioned during Phase III and Phase IV(1996). The signal conditioners were used during Phase IV(1997).

Channel	Description
215-221 (odd), 225-241 (odd)	Blade, root, yaw moment and low-speed shaft strain gages
Location	Rotor package
Input level	Isolated strain gage 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 gages 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 ±2mV Custom built by Embedded Systems

Digital Input / Output

Channel	Description
243-249 (odd), 253-261 (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

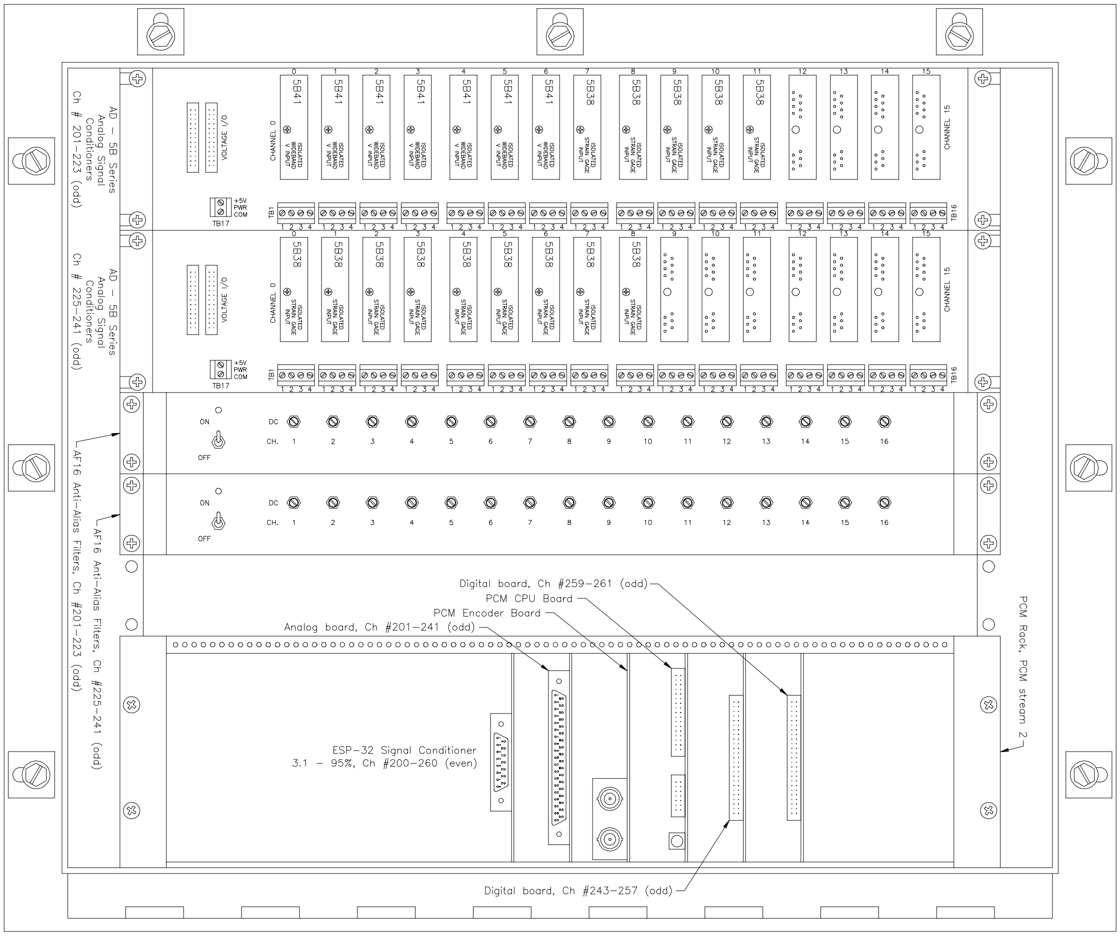


Figure B.20. Rotor based PCM enclosure.

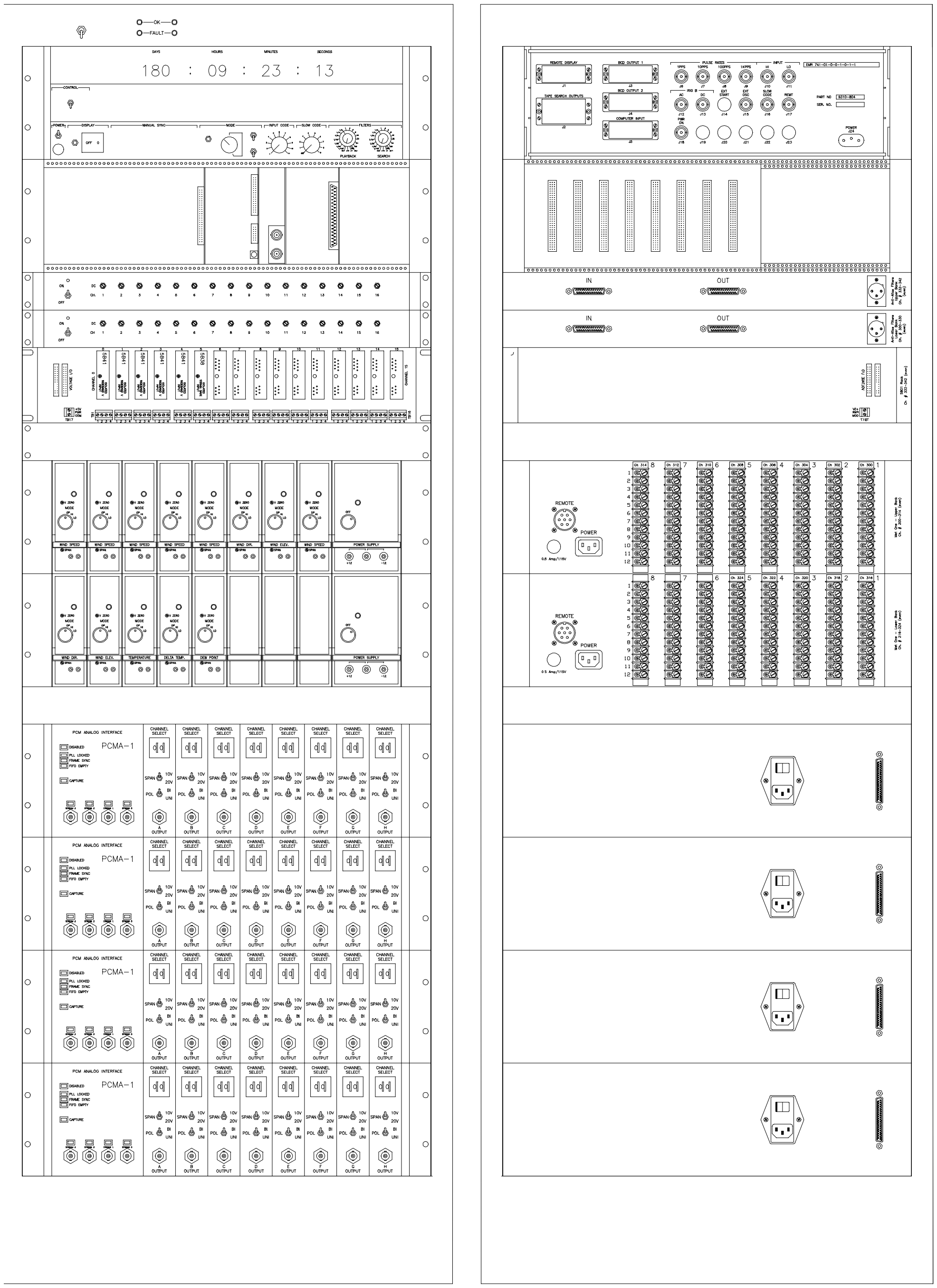


Figure B.21. Ground based PCM rack, front view and rear view.

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 and digital reference pressure channels (213, 259, 261) may be observed using *barsall.exe*, *onebar.exe*, or *strip.exe*. These channels are not recorded in the **.dat* file which is necessary for all further processing.

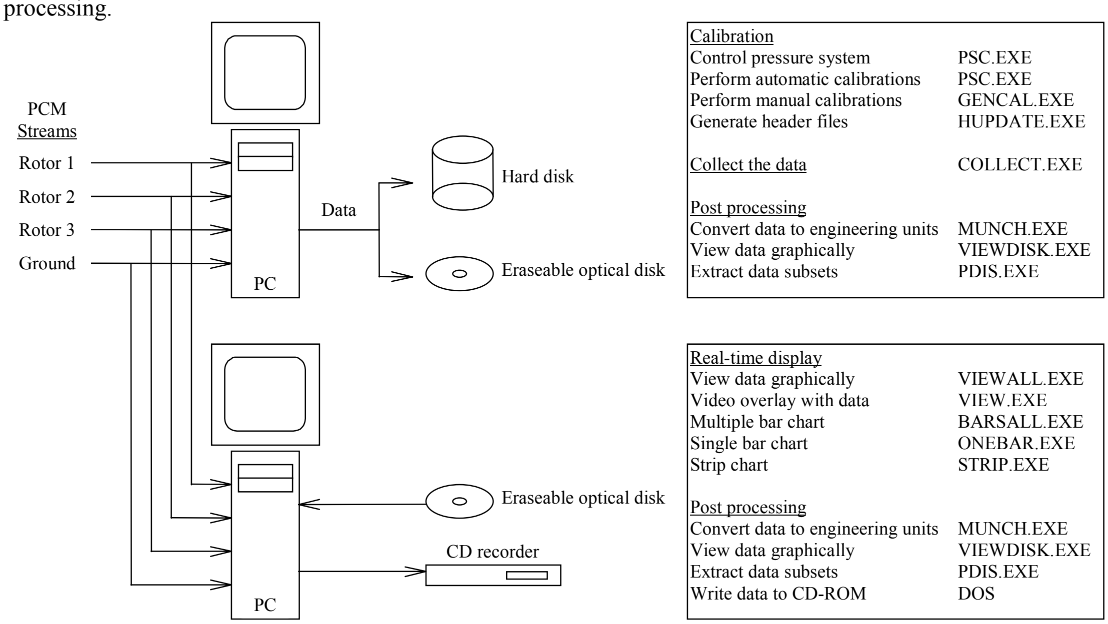


Figure B.22. Signal path from PCM streams to useable data.

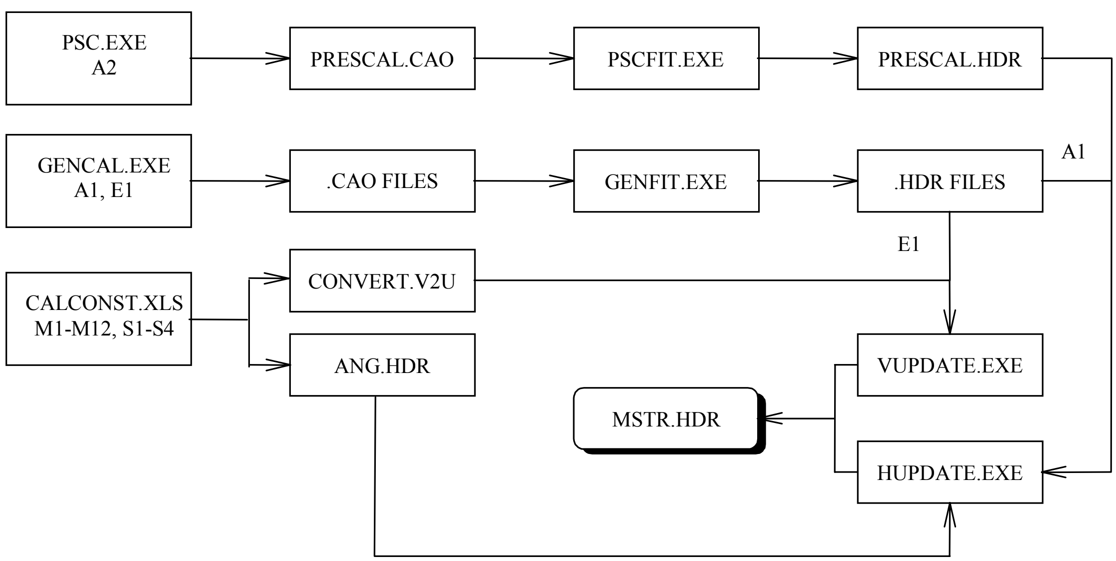


Figure B.23. Production of calibration and header files (calibration procedures are summarized on p. B-61).

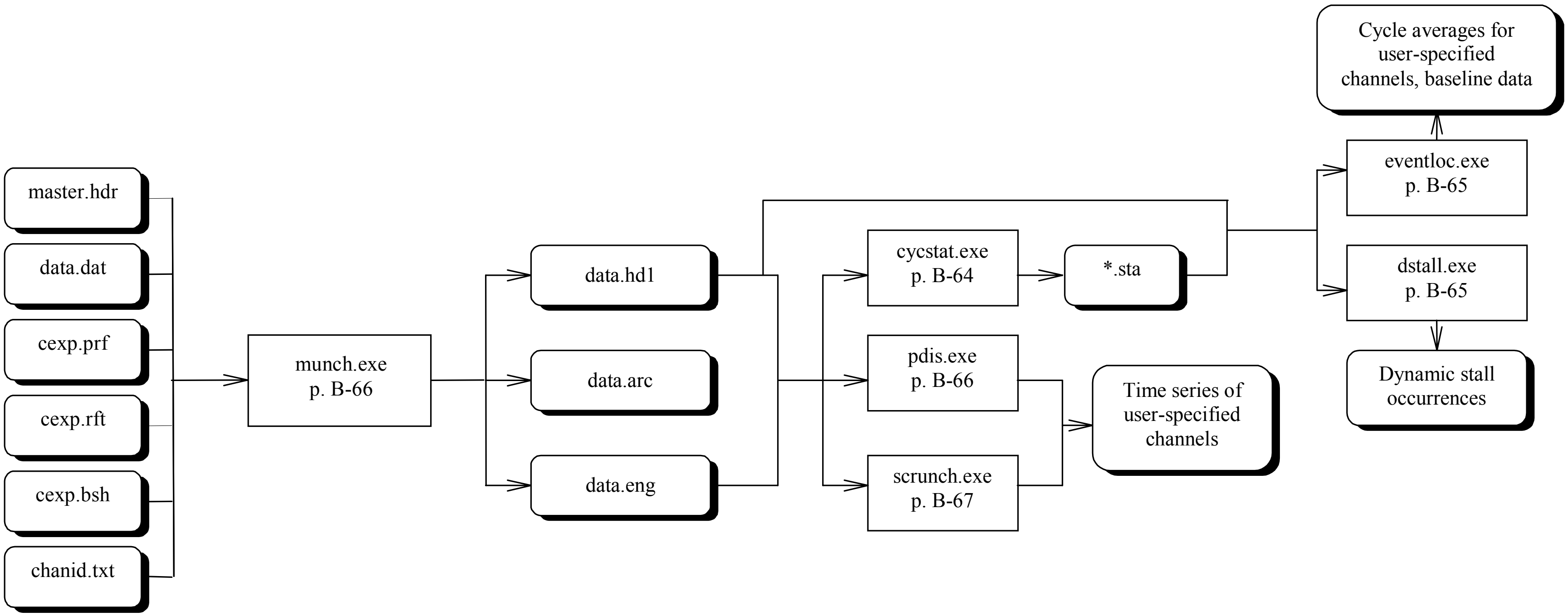


Figure B.24. Data processing flow chart.

Applied Load Calibration - (A1, A2)

The pressure transducers and the strain gages 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 B-1. Strain gage calibration file names.

Channel Number	ID Code	File Name*	Calibration Range	Voltage Increment
225	B1RFB	*b1fpu.cao, b1fnu.cao*	0 – 100 lb	20 lb
		b1fpd.cao, b1fnd.cao	100 – 0 lb	
227, 241	B1REB, LSSTQ	*b1epu.cao, b1enu.cao*	0 – 100 lb	20 lb
		b1epd.cao, b1end.cao	100 – 0 lb	
229	B2RFB	*b2fpu.cao, b2fnu.cao*	0 – 100 lb	20 lb
		b2fpd.cao, b2fnd.cao	100 – 0 lb	
231, 241	B2REB, LSSTQ	*b2epu.cao, b2enu.cao*	0 – 100 lb	20 lb
		b2epd.cao, b2end.cao	100 – 0 lb	
233, 237	B3RFB, LSSXXB	*b3fpu.cao, b3fnu.cao*	0 – 100 lb	20 lb
		b3fpd.cao, b3fnd.cao	100 – 0 lb	
235, 241	B3REB, LSSTQ	*b3epu.cao, b3enu.cao*	0 – 100 lb	20 lb
		b3epd.cao, b3end.cao	100 – 0 lb	
342	NAYM	*b3ympu.cao, b3ymnu.cao,*	0 – 100 lb	20 lb
		b3ympd.cao, b3ymnd.cao	100 – 0 lb	
225, 227, 229, 231, 233, 235, 237, 239, 241	B1RFB, B1REB, B2RFB, B2REB, B3RFB, B3REB, LSSXXB, LSSYYB, LSSTQ	*zero1.cao,* *zero2.cao*	0 – 150° 180 – 330°	30° 30°

* p indicates load in positive direction; n indicates load in negative direction

Manufacturer Specifications - (M1-M12)

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 producing the slope and offset values stored in *master.hdr*.

Single Point Offset Determination - (S1-S4)

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.

Electronics 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 electronics 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 B-2. Electronics 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 electronics 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 gages 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.

Pitch System

Prior to the portion of Phase IV data collected during the spring of 1997, the pitch system of the turbine was calibrated to ensure that all blades pitched to the same angle. The Angle Star was used to measure the pitch angle of all three blades for a nominal angle. The mechanism in the hub of the turbine was adjusted until all three blades were within 0.1° of each other. The following table contains the values of the angles after the adjustments were made.

Table B.3. Pitch System Calibration Results.

Blade	Pitch Angle (°)		
1	1.0	0.4	11.0
2	1.1	0.5	10.9
3	1.1	0.5	10.9

Precision Voltage Generator

The electronic path calibrations were performed using an HP 3245A Universal Source which was calibrated by the manufacturer on 7/10/90.

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 providing the total weight of the blade. However, after the Phase IV (1996) blade weights were measured, one of the scales was found to read 5% high. The root-end measurements were reduced by 5% in the results reported in Appendix A. These weights compare with the blade weights obtained prior to the second series of Phase IV data collection in 1997.

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 which 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 data base 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 gage 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. Insure 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 under 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 gage 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*, *p1redo.tbl…p5redo.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 (*p1redo.tbl…p5redo.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.

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).

```
5
349,"Azimuth","deg",2,9.84375,.087890625,0,0,0,0,-99999,99999,0,"M"
351,"Yaw","deg",2,218.435546875,.087890625,0,0,0,0,-99999,99999,0,"M"
253,"Pitch 1","deg",2,-20.21484375,.087890625,0,0,0,0,-99999,99999,0,"M"
255,"Pitch 2","deg",2,-22.5,.087890625,0,0,0,0,-99999,99999,0,"M"
257,"Pitch 3","deg",2,-23.02734375,.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°=	2160	counts	0.087890625	° / count	9.84375	0.087890625	*counts	349	deg
Yaw	292°=	837	counts	0.087890625	° / count	218.4355469	0.087890625	*counts	351	deg
Pitch 1	0°=	230	counts	0.087890625	° / count	-20.21484375	0.087890625	*counts	253	deg
Pitch 2	0°=	256	counts	0.087890625	° / count	-22.5	0.087890625	*counts	255	deg
Pitch 3	0°=	262	counts	0.087890625	° / count	-23.02734375	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°=	2.6	volts	72	° / V	104.8	72	*volts	310	deg
Wind direction - S	292°=	2.596	volts	72	° / V	105.088	72	*volts	316	deg
Wind elevation - N	0°=	2.3855	volts	-24.00211219	° / V	57.25703862	-24.00211219	*volts	312	deg
Wind elevation - S	0°=	2.413	volts	-23.99736029	° / V	57.90563038	-23.99736029	*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 2 Flap Accel	0 g=	0	volts	200.5	mV/g	0	48.87780549	*volts	205	mps2
Blade 2 Edge Accel	0 g=	0	volts	201	mV/g	0	48.75621891	*volts	207	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.

```
27
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",2,104.8,72
316,"Wind direction - S","deg",2,105.088,72
312,"Wind elevation - N","deg",2,57.2570386193985,-24.0021121858724
318,"Wind elevation - S","deg",2,57.9056303806581,-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
205,"Blade 2 Flap Accel","mps2",2,0,48.8778054862843
207,"Blade 2 Edge Accel","mps2",2,0,48.7562189054726
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.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.exe*. 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.exe* 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, and so forth.

```
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.exe*. A linear regression was performed on the data added to *ground2.cao* during the *gencal.exe* program. The resulting slope and offset are inserted in the appropriate locations of the **.hdr* file. This file is then used in conjunction 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
235,312500,0.00192
000, "P130100","Pressure #1, 30% span, trailing ","Cp",2,2798.300049,-
1.416100,,,,0.260121,0.767966,-0.106536,0.121577,"M",890,1606,0
001, "P147100","Pressure #1, 47% span, trailing ","Cp",2,-
2822.600098,1.457300,,,,0.115069,0.447418,-0.291254,0.111500,"M",1303,1513,0
002, "P43080U","Pressure #4, 30% span, 80% upper ","Cp",2,2810.000000,-
1.405000,,,,0.029517,0.683518,-0.326128,0.160214,"M",894,1059,0
003, "P44780U","Pressure #4, 47% span, 80% upper ","Cp",2,-
2864.500000,1.421500,,,,-0.036422,0.295358,-0.447499,0.113975,"M",438,1272,0
004, "P63068U","Pressure #6, 30% span, 68% upper ","Cp",2,2907.300049,-
1.415700,,,,-0.094158,0.520208,-0.550541,0.172850,"M",892,617,0
005, "P64768U","Pressure #6, 47% span, 68% upper ","Cp",2,-
2965.800049,1.437800,,,,-0.139411,0.233049,-0.433362,0.137785,"M",437,1523,0
```

***.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 239 channels in Phase III and 262 channels in Phase IV. 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 2 m is calculated. The yaw error angle based upon 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 8-bit error byte. These files are stored in binary format.

Appendix C

Instrumentation Summaries

Table C.1. Phase II Instrumentation Summary

Channel	ID Code	Description	Sensor Location	Measurement Type and Units	Sensor Type
000-032	**Ptt63ccc** **Ptt52ccc** **Ptt58ccc** **Ptt69ccc**	Surface pressures at 63%, 52%, 58%, and 69% 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
033	**TP67**	Total pressure probe at 67% span	Within blade 3 at approximately 63% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
124-154	**Ptt80ccc** **Ptt74ccc** **Ptt69ccc**	Surface pressures at 80%, 74%, and 69% 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
155	**TP86**	Total pressure probe at 86% span	Within blade 3 at approximately 80% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
200-227	**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
228	**TP34**	Total pressure probe at 34% span	Within blade 3 at approximately 30% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
229-257	**Ptt47ccc** **Ptt41ccc**	Surface pressures at 47%, and 41% 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
258	**TP51**	Total pressure probe at 51% span	Within blade 3 at approximately 47% span	Differential pressure, Pa	32 channel scanning, electronic pressure transducer
034	**80LFA**	80% Local Flow Angle	Local flow angle flag at 80% span	Angular position, deg	Rotary variable differential transducer
035	**63LFA**	63% Local Flow Angle	Local flow angle flag at 63% span	Angular position, deg	Rotary variable differential transducer
037	**30LFA**	30% Local Flow Angle	Local flow angle flag at 30% span	Angular position, deg	Rotary variable differential transducer
38	**VPAWS1**	VPA Prop Vane Speed WS-1 (12:00)	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Prop vane
39	**VPAWS2**	VPA Prop Vane Speed WS-2 (1:30)	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Prop vane
40	**VPAWS3**	VPA Prop Vane Speed WS-3 (3:00)	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Prop vane
41	**VPAWS4**	VPA Prop Vane Speed WS-4 (4:30)	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Prop vane
42	**VPAWS5**	VPA Prop Vane Speed WS-5 (6:00)	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Prop vane
43	**VPAWS6**	VPA Prop Vane Speed WS-6 (7:30)	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Prop vane
44	**VPAWS7**	VPA Prop Vane Speed WS-7 (9:00)	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Prop vane
45	**VPAWS8**	VPA Prop Vane Speed WS-8 (10:30)	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Prop vane
46	**VPAWS9**	VPA Prop Vane Speed WS-9 Hub Height	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Prop vane
47	**VPAWD9**	VPA Prop Vane Direction WD-9 Hub Height	Vertical Plane Array, 1 D upwind	Wind direction, deg	Prop vane
48	**VPAWS12**	VPA Bi-Vane Speed WS-12 (3:00 @100%)	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Bi-vane

Table C.1. Phase II Instrumentation Summary (continued)

Channel	ID Code	Description	Sensor Location	Measurement Type and Units	Sensor Type
49	**VPAWD12**	VPA Bi-Vane Direction WD-12 (3:00 @100%)	Vertical Plane Array, 1 D upwind	Wind direction, deg	Bi-vane
50	**VPAWE12**	VPA Bi-Vane Elevation WE-12 (3:00 @100%)	Vertical Plane Array, 1 D upwind	Wind elevation, deg	Bi-vane
51	**VPAWS13**	VPA Bi-Vane Speed WS-13 (9:00 @100%)	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Bi-vane
52	**VPAWD13**	VPA Bi-Vane Direction WD-13 (9:00 @100%)	Vertical Plane Array, 1 D upwind	Wind direction, deg	Bi-vane
53	**VPAWE13**	VPA Bi-Vane Elevation WE-13 (9:00 @100%)	Vertical Plane Array, 1 D upwind	Wind elevation, deg	Bi-vane
54	**VPAWS10**	VPA Prop Vane Speed WS-10 (12:00 @40%)	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Prop vane
55	**VPAWS11**	VPA Prop Vane Speed WS-11 (6:00 @40%)	Vertical Plane Array, 1 D upwind	Wind speed, m/s	Prop vane
56	**B3AZI**	Low Speed Shaft Azimuth Angle	Blade 3 hub/nacelle	Angular position, deg	Pulse/revolution incremental encoder
57	**YAWMOM**	Yaw Moment	Arm of yaw brake	Bending moment, Nm	Strain gauge
58	**TBEWAX**	Tower Bending about East-West Axis (X)	Tower at height of 12 m	Bending moment, Nm	Strain gauge
59	**TBNSAY**	Tower Bending about North-South Axis (Y)	Tower at height of 12 m	Bending moment, Nm	Strain gauge
60	**YAW**	Yaw Angle	Tower/nacelle attachment	Angular position, deg	Gear-driven potentiometer
61	**GENPOW**	Generator Power	Nacelle bed plate	Generator power, kW	AC Watt transducer
102	**LMSA17M**	Sonic Anemometer Channel A	Local met tower, 1 D upwind	Individual component of wind	Three-axis, sonic anemometer
103	**LMSB17M**	Sonic Anemometer Channel B	Local met tower, 1 D upwind	Individual component of wind	Three-axis, sonic anemometer
104	**LMSC17M**	Sonic Anemometer Channel C	Local met tower, 1 D upwind	Individual component of wind	Three-axis, sonic anemometer
105	**B3ARFB**	Strain Blade 3A, root flap bending	Blade 3 pitch shaft (8% span)	Bending moment, Nm	Strain gauge
106	**B3BRFB**	Strain Blade 3B, root flap bending	Blade 3 pitch shaft (8% span)	Bending moment, Nm	Strain gauge
107	**B1RFB**	Strain Blade 1, root flap bending	Blade 2 pitch shaft (8% span)	Bending moment, Nm	Strain gauge
108	**B2RFB**	Strain Blade 2, root flap bending	Blade 1 pitch shaft (8% span)	Bending moment, Nm	Strain gauge
109	**B320FB**	Strain Blade 3, 20% flap bending	Skin of blade 3 at 20% span	Bending moment, Nm	Strain gauge
110	**B340FB**	Strain Blade 3, 40% flap bending	Skin of blade 3 at 40% span	Bending moment, Nm	Strain gauge
111	**B350FB**	Strain Blade 3, 50% flap bending	Skin of blade 3 at 50% span	Bending moment, Nm	Strain gauge
112	**B370FB**	Strain Blade 3, 70% flap bending	Skin of blade 3 at 70% span	Bending moment, Nm	Strain gauge
113	**B390FB**	Strain Blade 3, 90% flap bending	Skin of blade 3 at 90% span	Bending moment, Nm	Strain gauge
114	**B3AREB**	Strain Blade 3, root edge bending	Blade 3 pitch shaft (8% span)	Bending moment, Nm	Strain gauge
115	**B320EB**	Strain Blade 3, 20% edge bending	Skin of blade 3 at 20% span	Bending moment, Nm	Strain gauge
116	**B350EB**	Strain Blade 3, 50% edge bending	Skin of blade 3 at 50% span	Bending moment, Nm	Strain gauge
117	**70TQ**	70% blade torque	Skin of blade 3 at 70% span	Torque, Nm	Strain gauge
118	**RTTQ**	Root torque (link)	Blade 3 pitch shaft (8% span)	Torque, Nm	Strain gauge
119	**50TSN**	Blade 3 Torsion at 50% Span	Skin of blade 3 at 50% span	Torque, Nm	Strain gauge
120	**LSSXXB**	Strain X-X LSS bending	Low speed shaft	Bending moment, Nm	Strain gauge - 350 Ohm
121	**LSSYYB**	Strain Y-Y LSS bending	Low speed shaft	Bending moment, Nm	Strain gauge - 350 Ohm
122	**LSSTQA**	Strain LSS torque A	Low speed shaft	Torque, Nm	Strain gauge - 350 Ohm
123	**LSSTQB**	Strain LSS torque B	Low speed shaft	Torque, Nm	Strain gauge - 350 Ohm

Table C.1. Phase II Instrumentation Summary (continued)

Channel	ID Code	Description	Sensor Location	Measurement Type and Units	Sensor Type
156	ABSRP	Absolute reference pressure	Rotating instrumentation package	Reference pressure, Pa	Analog pressure transducer
Not recorded		Differential reference pressure	Rotating instrumentation package	Differential pressure, Pa	Analog differential pressure transducer
157	B3PITCH	Blade 3 Pitch angle	Blade 3 blade/hub attachment	Angular position, deg	Gear-driven potentiometer
300	NMWD5M	North met WD 5 m	North met tower, 500 m upwind	Wind direction, deg	
301	NMWS5M	North met WS 5 m	North met tower, 500 m upwind	Wind speed, m/s	
302	NMWD10M	North met WD 10 m	North met tower, 500 m upwind	Wind direction, deg	
304	NMWD20M	North met WD 20 m	North met tower, 500 m upwind	Wind direction, deg	
305	NMWS20M	North met WS 20 m	North met tower, 500 m upwind	Wind speed, m/s	
306	NMWD50M	North met WD 50 m	North met tower, 500 m upwind	Wind direction, deg	
307	NMWS50M	North met WS 50 m	North met tower, 500 m upwind	Wind speed, m/s	
308	NMT5M	North met Temperature 5 m	North met tower, 500 m upwind	Ambient air temperature, degC	
309	NMDT	North met Delta Temperature T50-T05	North met tower, 500 m upwind	Delta temperature, degC	
310	BARO	Barometric Pressure	North met tower, 500 m upwind	Ambient air pressure, Pa	Ambient air pressure transducer
311	DAY	Time-day	Data shed	Time-day	Time code generator
312	HOUR	Time-hour	Data shed	Time-hour	Time code generator
313	MINUTE	Time-minute	Data shed	Time-minute	Time code generator
314	SECOND	Time-second	Data shed	Time-second	Time code generator
315	MILLISEC	Time-millisecond	Data shed	Time-millisecond	Time code generator

Table C.1. Phase II Instrumentation Summary (continued)

Channel	ID Code	Power Requirement	Sensor Range	12-bit DAS Resolution	Manufacturer and Model Number	Analog Anti-Alias Filter (Butterworth)	Calibration Methods
000-032	**Ptt63ccc** **Ptt52ccc** **Ptt58ccc** **Ptt69ccc**	5Vdc, +/- 12Vdc	+/- 5 V = +/- 8274 Pa	4.0 Pa / bit	Pressure Systems, Inc. ESP-32		A2, A3
033	**TP67**	5Vdc, +/- 12Vdc	+/- 5 V = +/- 8274 Pa	4.0 Pa / bit	Pressure Systems, Inc. ESP-32		A2, A3
124-154	**Ptt80ccc** **Ptt74ccc** **Ptt69ccc**	5Vdc, +/- 12Vdc	+/- 5 V = +/- 8274 Pa	4.0 Pa / bit	Pressure Systems, Inc. ESP-32		A3, A4
155	**TP86**	5Vdc, +/- 12Vdc	+/- 5 V = +/- 8274 Pa	4.0 Pa / bit	Pressure Systems, Inc. ESP-32		A3, A4
200-227	**Ptt30ccc** **Ptt36ccc** **Ptt41ccc**	5Vdc, +/- 12Vdc	+/- 5 V = +/- 2970 Pa	1.5 Pa / bit	Pressure Systems, Inc. ESP-32		A2, A3
228	**TP34**	5Vdc, +/- 12Vdc	+/- 5 V = +/- 2970 Pa	1.5 Pa / bit	Pressure Systems, Inc. ESP-32		A2, A3
229-257	**Ptt47ccc** **Ptt41ccc**	5Vdc, +/- 12Vdc	+/- 5 V = +/- 2970 Pa	1.5 Pa / bit	Pressure Systems, Inc. ESP-32		A2, A3
258	**TP51**	5Vdc, +/- 12Vdc	+/- 5 V = +/- 2970 Pa	1.5 Pa / bit	Pressure Systems, Inc. ESP-32		A2, A3
034	**80LFA**	+/- 15 Vdc	+/- 10 V = -22 to 55 deg	0.02 deg / bit	Schaevitz Engineering R30D		M2
035	**63LFA**	+/- 15 Vdc	+/- 10 V = -22 to 55 deg	0.02 deg / bit	Schaevitz Engineering R30D		M2
037	**30LFA**	+/- 15 Vdc	+/- 10 V = -22 to 55 deg	0.02 deg / bit	Schaevitz Engineering R30D		M2
38	**VPAWS1**		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1
39	**VPAWS2**		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1
40	**VPAWS3**		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1
41	**VPAWS4**		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1
42	**VPAWS5**		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1
43	**VPAWS6**		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1
44	**VPAWS7**		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1
45	**VPAWS8**		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1
46	**VPAWS9**		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1
47	**VPAWD9**		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 21003	2 Hz	A1, M6
48	**VPAWS12**		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1

Table C.1. Phase II Instrumentation Summary (continued)

Channel	ID Code	Power Requirement	Sensor Range	12-bit DAS Resolution	Manufacturer and Model Number	Analog Anti-Alias Filter (Butterworth)	Calibration Methods
49	VPAWD12		0 to 2 V = 0 to 360 deg	0.088 deg / bit	R. M. Young 21003	2 Hz	A1, M6
50	VPAWE12		0 to 2 V = +/- 50 deg	0.024 deg / bit	R. M. Young 21003	2 Hz	A1, M7
51	VPAWS13		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1
52	VPAWD13		0 to 2 V = 0 to 360 deg	0.088 deg / bit	R. M. Young 21003	2 Hz	A1, M6
53	VPAWE13		0 to 2 V = +/- 50 deg	0.024 deg / bit	R. M. Young 21003	2 Hz	A1, M7
54	VPAWS10		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1
55	VPAWS11		0 to 10 V = 0 to 37 m/s	0.009 m/s / bit	R. M. Young 8003	2 Hz	A1, E1
56	B3AZI		0 to 5 V = 0 to 360 deg	0.088 deg / bit	Trump Ross 512	130 Hz	A1, M5
57	YAWMOM	5 Vdc	+/- 24.75 mV = +/- 3500 Nm	1.7 Nm / bit	Measurements Group, Inc.	40 Hz	A1, M10
58	TBEWAX	5 Vdc	+/- 5.05 mV = +/- 55000 Nm	27 Nm / bit	Measurements Group, Inc.	40 Hz	A1, M9
59	TBNSAY	5 Vdc	+5.03 to -5 mV = +/- 55000 Nm	27 Nm / bit	Measurements Group, Inc.	40 Hz	A1, M9
60	YAW		0 to 10 V = 0 to 360 deg	0.088 deg / bit		10 Hz	A1, M4
61	GENPOW	240 Vac	+/- 5 V = +/- 40 kW	0.02 kW / bit	Ohio Semitronics, Inc. PC5-63C	55 Hz	A1, E6
102	LMSA17M				Kaijo-Denki	12 Hz	
103	LMSB17M				Kaijo-Denki	12 Hz	
104	LMSC17M				Kaijo-Denki	12 Hz	
105	B3ARFB	5 Vdc	+/- 6.25 mV = +/- 3200 Nm	1.6 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
106	B3BRFB	5 Vdc	+/- 5.0 mV = +/- 3200 Nm	1.6 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
107	B1RFB	5 Vdc	+/- 5.0 mV = +/- 3200 Nm	1.6 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
108	B2RFB	5 Vdc	+/- 6.25 mV = +/- 3200 Nm	1.6 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
109	B320FB	5 Vdc	+/- 5.0 mV = +/- 3000 Nm	1.5 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
110	B340FB	5 Vdc	+/- 10.0 mV = +/- 2300 Nm	1.1 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
111	B350FB	5 Vdc	+/- 7.0 mV = +/- 1400 Nm	0.7 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
112	B370FB	5 Vdc	+/- 5.0 mV = +/- 800 Nm	0.4 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
113	B390FB	5 Vdc	+/- 2.5 mV = +/- 300 Nm	0.1 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
114	B3AREB	5 Vdc	+/- 6.25 mV = +/- 3200 Nm	1.6 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
115	B320EB	5 Vdc	+/- 7.0 mV = +/- 3000 Nm	1.5 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
116	B350EB	5 Vdc	+/- 10.0 mV = +/- 1400 Nm	0.7 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
117	70TQ	5 Vdc	+/- 2.5 mV = +/- 1100 Nm	0.5 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
118	RTTQ	5 Vdc	+/- 2.5 mV = +/- 205 Nm	0.1 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
119	50TSN	5 Vdc	+/- 2.5 mV = +/- 300 Nm	0.1 Nm / bit	Measurements Group, Inc.	40 Hz	A2, M8
120	LSSXXB	10 Vdc	+/- 10.0 mV = +/- 13000 Nm	6.3 Nm / bit	Measurements Group, Inc. CEA-06-250UW-350	40 Hz	A2, M8
121	LSSYYB	10 Vdc	+/- 10.0 mV = +/- 13000 Nm	6.3 Nm / bit	Measurements Group, Inc. CEA-06-250UW-350	40 Hz	A2, M8
122	LSSTQA	10 Vdc	+/- 5.0 mV = +/- 6500 Nm	3.2 Nm / bit	Measurements Group, Inc. CEA-06-250US-350	40 Hz	A2, M8
123	LSSTQB	10 Vdc	+/- 5.0 mV = +/- 6500 Nm	3.2 Nm / bit	Measurements Group, Inc. CEA-06-250US-350	100 Hz	A2, M8

Table C.1. Phase II Instrumentation Summary (concluded)

Channel	ID Code	Power Requirement	Sensor Range	12-bit DAS Resolution	Manufacturer and Model Number	Analog Anti-Alias Filter (Butterworth)	Calibration Methods
156	ABSRP		0 to 5 V = 80000 to 110000 Pa	7.3 Pa / bit	Setra Systems, Inc. 270	1.5 kHz	E3
Not recorded			+/- 2.5 V = +/- 1866 Pa	0.9 Pa / bit	Setra Systems, Inc. 239	1.5 kHz	E4
157	B3PITCH		0 to 5 V = -106 to 71 deg	0.04 deg / bit			M3
300	NMWD5M	+/- 12 Vdc	0 to 5 V = 0 to 360 deg	0.088 deg / bit	Teledyne Geotech WS-201, 21.21	1 Hz	
301	NMWS5M	+/- 12 Vdc	0 to 5 V = 0 to 90 m/s	0.02 m/s / bit	Teledyne Geotech WS-201, 21.11	1 Hz	M1, E1
302	NMWD10M	+/- 12 Vdc	0 to 5 V = 0 to 360 deg	0.088 deg / bit	Teledyne Geotech WS-201, 21.21	1 Hz	
304	NMWD20M	+/- 12 Vdc	0 to 5 V = 0 to 360 deg	0.088 deg / bit	Teledyne Geotech WS-201, 21.21	1 Hz	
305	NMWS20M	+/- 12 Vdc	0 to 5 V = 0 to 90 m/s	0.02 m/s / bit	Teledyne Geotech WS-201, 21.11	1 Hz	M1, E1
306	NMWD50M	+/- 12 Vdc	0 to 5 V = 0 to 360 deg	0.088 deg / bit	Teledyne Geotech WS-201, 21.21	1 Hz	
307	NMWS50M	+/- 12 Vdc	0 to 5 V = 0 to 90 m/s	0.02 m/s / bit	Teledyne Geotech WS-201, 21.11	1 Hz	M1, E1
308	NMT5M	+/- 12 Vdc	0 to 5 V = +/- 50 degC	0.02 degC / bit	Teledyne Geotech WS-201, 21.32	1 Hz	M1, E5
309	NMDT	+/- 12 Vdc	0 to 5 V = -4.4 to 6.7 degC	0.003 degC / bit	Teledyne Geotech WS-201, 21.32	1 Hz	M1, E4
310	BARO		0 to 5 V = 70000 to 93000 Pa	5.6 Pa / bit	YSI 2014-21/27	1 Hz	M1, E3
311	DAY						
312	HOUR						
313	MINUTE						
314	SECOND						
315	MILLISEC						

Note: Calibration methods described in Phase I Final Report (Butterfield et al. 1992)

Table C.2. Phase III and Phase IV 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
056, 057*	TP34, TP50	Total pressure probes at 34% and 51% span The header files incorrectly list a probe at 50% span	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
100-151 (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
156*	TP67	Total pressure probe at 67% span	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
101-145 (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
157*	TP83	Total pressure probe at 84% span The header files incorrectly list a probe at 83% span	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
205	B2ACFL	Accelerometer Blade 2-Flap	Tip of blade 2	Linear flap acceleration, mps2	Accelerometer
207	B2ACED	Accelerometer Blade 2-Edge	Tip of blade 2	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*	B325FB	Strain Blade 3 25% flap bending	Skin of blade 3 at 25% span	Bending moment, Nm	Strain gauge
217*	B325EB	Strain Blade 3 25% edge bending	Skin of blade 3 at 25% span	Bending moment, Nm	Strain gauge
219*	B360FB	Strain Blade 3 60% flap bending	Skin of blade 3 at 60% span	Bending moment, Nm	Strain gauge
221*	B360EB	Strain Blade 3 60% edge bending	Skin of blade 3 at 60% span	Bending moment, Nm	Strain gauge
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

Table C.2. Phase III and Phase IV Instrumentation Summary (continued)

Channel	ID Code	Description	Sensor Location	Measurement Type and Units	Sensor Type	Power Requirement
229	B2RFB	Strain Blade 2 root flap bending	Blade 2 pitch shaft (8% span)	Bending moment, Nm	Strain gauge - 350 Ohm	+/- 10 Vdc
231	B2REB	Strain Blade 2 root edge bending	Blade 2 pitch shaft (8% span)	Bending moment, Nm	Strain gauge - 350 Ohm	+/- 10 Vdc
233	B3RFB	Strain Blade 3 root flap bending	Blade 3 pitch shaft (8% span)	Bending moment, Nm	Strain gauge - 350 Ohm	+/- 10 Vdc
235	B3REB	Strain Blade 3 root edge bending	Blade 3 pitch shaft (8% span)	Bending moment, Nm	Strain gauge - 350 Ohm	+/- 10 Vdc
237	LSSXXB	Strain X-X LSS bending	Low speed shaft	Bending moment, Nm	Strain gauge - 350 Ohm	+/- 10 Vdc
239	LSSYYB	Strain Y-Y LSS bending	Low speed shaft	Bending moment, Nm	Strain gauge - 350 Ohm	+/- 10 Vdc
241	LSSTQ	Strain LSS torque	Low speed shaft	Torque, Nm	Strain gauge - 350 Ohm	+/- 10 Vdc
243*	30LFA	Digital 30% LFA	Local flow angle flag at 30% span	Angular position, deg	Digital position encoder	+/- 15 Vdc, 5V
245*	47LFA	Digital 47% LFA	Local flow angle flag at 47% span	Angular position, deg	Digital position encoder	+/- 15 Vdc, 5V
247*	63LFA	Digital 63% LFA	Local flow angle flag at 63% span	Angular position, deg	Digital position encoder	+/- 15 Vdc, 5V
249*	80LFA	Digital 80% LFA	Local flow angle flag at 80% span	Angular position, deg	Digital position encoder	+/- 15 Vdc, 5V
253	B1PITCH	Digital Blade 1 pitch	Blade 1 root/hub attachment	Angular position, deg	Digital position encoder	+/- 15 Vdc, 5V
255	B2PITCH	Digital Blade 2 pitch	Blade 2 root/hub attachment	Angular position, deg	Digital position encoder	+/- 15 Vdc, 5V
257	B3PITCH	Digital Blade 3 pitch	Blade 3 root/hub attachment	Angular position, deg	Digital position encoder	+/- 15 Vdc, 5V
259, 261	Not recorded	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	12 Vdc
300	LMWS24M	Local met WS 24.38 m	Central MET Tower	Wind speed, m/s	Cup anemometer	+/- 12 Vdc
302	LMWS17M	Local met WS 17.02 m (hub height)	Central MET Tower	Wind speed, m/s	Cup anemometer	+/- 12 Vdc
304	LMWS10M	Local met WS 10.06 m	Central MET Tower	Wind speed, m/s	Cup anemometer	+/- 12 Vdc
306	LMWS2M	Local met WS 2.4 m	Central MET Tower	Wind speed, m/s	Cup anemometer	+/- 12 Vdc
308	NLMWS17M	N local met WS 17.02 m (hub height)	North MET Tower	Wind speed, m/s	Cup anemometer	+/- 12 Vdc
310	NLMWD17M	N local met WD 17.02 m (hub height)	North MET Tower	Wind Direction, deg	Bi-Vane anemometer	+/- 12 Vdc
312	NLMWE17M	N local met WE 17.02 m (hub height)	North MET Tower	Wind Elevation, deg	Bi-Vane anemometer	+/- 12 Vdc
314	SLMWS17M	S local met WS 17.02 m (hub height)	South MET Tower	Wind speed, m/s	Cup anemometer	+/- 12 Vdc
316	SLMWD17M	S local met WD 17.02 m (hub height)	South MET Tower	Wind Direction, deg	Bi-Vane anemometer	+/- 12 Vdc
318	SLMWE17M	S local met WE 17.02 m (hub height)	South MET Tower	Wind Elevation, deg	Bi-Vane anemometer	+/- 12 Vdc
320	LMT2M	Local met temperature 2.4m	Central MET Tower	Ambient air temperature, degC	Platinum resistance element (100 Ohm)	+/- 12 Vdc
322***	LMT24M	Local met temperature 24.38m	Central MET Tower	Ambient air temperature, degC	Platinum resistance element (100 Ohm)	+/- 12 Vdc
322	LMDT	Local met Delta Temperature	Central MET Tower	Delta temperature, degC	Platinum resistance element (100 Ohm)	+/- 12 Vdc
324	LMDP2M	Local met dewpoint 2.4m	Central MET Tower	Dewpoint temperature, degC	Dewpoint temperature sensor	+/- 12 Vdc
326	LMSU17M	Local met sonic channel U 17.02 m	Central MET Tower	Horizontal wind speed perpendicular to rotor plane, m/s	Sonic Anemometer	120 Vac
328	LMSV17M	Local met sonic channel V 17.02 m	Central MET Tower	Horizontal wind speed parallel to rotor plane, m/s	Sonic Anemometer	120 Vac
330	LMSW17M	Local met sonic channel W 17.02 m	Central MET Tower	Vertical wind speed, m/s	Sonic Anemometer	120 Vac

Table C.2. Phase III and Phase IV Instrumentation Summary (continued)

Channel	ID Code	Description	Sensor Location	Measurement Type and Units	Sensor Type	Power Requirement
332	GENPOW	Generator power	Nacelle bed plate	Generator power, kW	AC Watt transducer	240 Vac
334	BARO	Barometric pressure	Data shed	Ambient air pressure, Pa	Ambient air pressure transducer	15Vdc
336	NAACYW	Nacelle Accelerometer Yaw	Nacelle bed plate	Linear yaw acceleration, m/s2	Accelerometer	15Vdc
338	NAACFA	Nacelle Accelerometer Fore-Aft	Nacelle bed plate	Linear fore-aft acceleration, m/s2	Accelerometer	15Vdc
340	NAACPI	Nacelle Accelerometer Pitch	Nacelle bed plate	Linear pitch acceleration, m/s2	Accelerometer	15Vdc
342**	NAYM	Nacelle Yaw Moment	Arm of yaw brake	Bending moment, Nm	Strain gauge	+/- 10 Vdc
349	B3AZI	Blade azimuth angle	Blade 3 hub/nacelle attachment	Angular position, deg	Digital position encoder	15Vdc
351	YAW	Yaw angle	Tower/nacelle attachment	Angular position, deg	Digital position encoder	15Vdc
353	DAY	Clock - day	Data shed	Time, day	Time code generator	120 Vac
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		

* Phase III Only

** Phase IV Only

*** Data1-data6 only

Table C.2. Phase III and Phase IV Instrumentation Summary (continued)

Channel	ID Code	Power Requirement	Sensor Range	12-bit DAS Resolution	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
056, 057*	TP34, TP50	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
100-151 (even)	Ptt63ccc Ptt69ccc Ptt74ccc	5Vdc, +/- 12Vdc	+/- 5 V = +/- 5000 Pa	2.4 Pa / bit	+/- 0.1 % full scale (static)	Pressure Systems, Inc. ESP-32
156*	TP67	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
101-145 (odd)	Ptt80ccc Ptt85ccc Ptt90ccc	5Vdc, +/- 12Vdc	+/- 5 V = +/- 10342 Pa	5.0 Pa / bit	+/- 0.1 % full scale (static)	Pressure Systems, Inc. ESP-32
157*	TP83	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
205	B2ACFL	15Vdc	+/- 2 V = +/- 10g	0.024 mps2 / bit	200 mV/g	Endevco Corporation 7290A-10
207	B2ACED	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*	B325FB	+/- 10 Vdc	0-4096 counts=+/- 9500 Nm	4.6 Nm / bit		Measurements Group, Inc.
217*	B325EB	+/- 10 Vdc	0-4096 counts=+/- 18000 Nm	9.0 Nm / bit		Measurements Group, Inc.
219*	B360FB	+/- 10 Vdc	0-4096 counts=+/- 7000 Nm	3.3 Nm / bit		Measurements Group, Inc.
221*	B360EB	+/- 10 Vdc	0-4096 counts=+/- 9000 Nm	4.4 Nm / bit		Measurements Group, Inc.
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

Table C.2. Phase III and Phase IV Instrumentation Summary (continued)

Channel	ID Code	Power Requirement	Sensor Range	12-bit DAS Resolution	Sensor Accuracy	Manufacturer and Model Number
229	B2RFB	+/- 10 Vdc	0-4096 counts=+/- 16000 Nm	8 Nm / bit		Measurements Group, Inc. LWK-09-W250B-350
231	B2REB	+/- 10 Vdc	0-4096 counts=+/- 16000 Nm	8 Nm / bit		Measurements Group, Inc. LWK-09-W250B-350
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
243*	30LFA	+/- 15 Vdc, 5V	0-4096 counts = 0-360 deg	0.088 deg / bit	12 bit +/- 0.1 deg +/- 1 LSB	Computer Conversions Corporation TDS12-F-1PC, TDS36-F-1PC
245*	47LFA	+/- 15 Vdc, 5V	0-4096 counts = 0-360 deg	0.088 deg / bit	12 bit +/- 0.1 deg +/- 1 LSB	Computer Conversions Corporation TDS12-F-1PC, TDS36-F-1PC
247*	63LFA	+/- 15 Vdc, 5V	0-4096 counts = 0-360 deg	0.088 deg / bit	12 bit +/- 0.1 deg +/- 1 LSB	Computer Conversions Corporation TDS12-F-1PC, TDS36-F-1PC
249*	80LFA	+/- 15 Vdc, 5V	0-4096 counts = 0-360 deg	0.088 deg / bit	12 bit +/- 0.1 deg +/- 1 LSB	Computer Conversions Corporation TDS12-F-1PC, TDS36-F-1PC
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	B2PITCH	+/- 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
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	Not recorded	12 Vdc	+/- 13,790 Pa	0.42 Pa/bit	0.01% 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***	LMT24M	+/- 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 Instruemnts 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 C.2. Phase III and Phase IV Instrumentation Summary (continued)

Channel	ID Code	Power Requirement	Sensor Range	12-bit DAS Resolution	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					

* Phase III Only

** Phase IV Only

*** Data1-data6 only

Table C.2. Phase III and Phase IV 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-39
056, 057*	TP34, TP50	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-39
052-060 (even)**	5Hx34	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-39
001-051 (odd)	Ptt47ccc Ptt52ccc Ptt58ccc	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-39
053-061 (odd)**	5Hx51	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-39
100-151 (even)	Ptt63ccc Ptt69ccc Ptt74ccc	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-41
156*	TP67	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-41
152-160 (even)**	5Hx67	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-41
101-145 (odd)	Ptt80ccc Ptt85ccc Ptt90ccc	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-42
157*	TP83	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-42
153-161 (odd)**	5Hx84	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-42
200-250 (even)	Ptt95ccc Ptt92ccc Ptt98ccc	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-42
252-260 (even)	5Hx91	+/- 5 Vdc multiplexed (Pressure Systems, Inc. ESP-32)		A2	B-42
201	B1ACFL	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-29
203	B1ACED	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-29
205	B2ACFL	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-29
207	B2ACED	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-29
209	B3ACFL	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-29
211	B3ACED	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-29
213	Not recorded	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter		B-44
215*	B325FB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-25
217*	B325EB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-25
219*	B360FB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-25
221*	B360EB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-25
225	B1RFB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-21
227	B1REB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-21

Table C.2. Phase III and Phase IV Instrumentation Summary (continued)

Channel	ID Code	Signal Conditioning	Analog Anti-Alias Filters	Calibration Methods	Page Number
229	B2RFB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-21
231	B2REB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-21
233	B3RFB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-21
235	B3REB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-21
237	LSSXXB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-26
239	LSSYYB	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-26
241	LSSTQ	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Bessel Filter	A1	B-26
243*	30LFA			M10, S4	B-37
245*	47LFA			M10, S4	B-37
247*	63LFA			M10, S4	B-37
249*	80LFA			M10, S4	B-37
253	B1PITCH			M9, S3	B-34
255	B2PITCH			M9, S3	B-34
257	B3PITCH			M9, S3	B-34
259, 261	Not recorded		Built into module	M11	B-45
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***	LMT24M	Temperature processor (Met One Instruments, 21.32A4)	Butterworth Filter	M5, E1	B-14
322	LMDT	Delta temperature processor (Teledyne ModS22 rev. E)	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 C.2. Phase III and Phase IV Instrumentation Summary (concluded)

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-32
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-29
338	NAACFA	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-29
340	NAACPI	+/- 1 Vdc to +/- 5 V dc (Analog Devices, Inc. 5B41-01)	Bessel Filter	M8, E1	B-29
342**	NAYM	+/- 30 mV to +/- 5V dc (Analog Devices, Inc. 5B38-01)	Butterworth Filter	A1	B-28
349	B3AZI			M9, S3	B-34
351	YAW			M9, S3	B-34
353	DAY			M12	B-47
355	HOUR			M12	B-47
357	MINUTE			M12	B-47
359	SECOND			M12	B-47
361	MILLISEC			M12	B-47

* Phase III Only

** Phase IV Only

*** Data1-data6 only

Appendix D

Data Summary Tables

Table D.1. Phase II Data Index.

Campaign	Mean Blade 3 Pitch (deg)	Mean H.H. Wind Speed (m/s)	Mean North Wind Direction (deg)	Mean South Wind Direction (deg)	Mean Richardson Number	Mean Yaw Error Angle (deg)	Comments	Problems
d6511	8.611	7.531	258.469	257.013	-0.2129	1.445		B, C, D, E, I
d6512	8.880	7.911	246.834	244.108	-0.2018	-4.827	1	B, C, D, E, I
d6521	8.874	7.635	243.387	240.726	-0.5079	4.144	1	B, C, D, E, I
d6522	8.812	4.583	263.776	262.966	-2.0207	-0.840	1	B, C, D, E, I
d6611	11.831	13.560	293.940	293.951	-0.0253	-4.662	1, 2, 3	A, B, C, D, E, F
d6612	11.801	11.183	298.828	299.091	-0.0297	-2.153	1, 2	A, B, C, D, E, F
d6621	11.657	8.407	301.113	301.715	-0.0256	-2.542	1, 2	A, B, C, D, E
d6622	11.654	8.650	297.560	297.459	-0.0262	-4.715	1, 2	A, B, C, D, E
d6631	11.702	10.399	286.521	287.049	-0.0406	-2.527	1, 2	A, B, C, D, E
d6632	11.623	9.050	289.359	290.370	-0.0523	-2.031	1, 2	A, B, C, D, E
d6711	11.944	9.418	316.079	316.753	-0.0649	-3.239		B, C, D, E
d6712	11.937	9.040	318.031	318.727	-0.0400	-1.321	1, 2	B, C, D, E
d6721	11.880	7.459	304.736	304.930	-0.0586	1.341		B, C, D, E
d6722	11.797	4.330	292.938	291.173	-0.1195	-8.262		B, C, D, E
d6731	11.938	10.373	296.839	296.224	-0.0138	0.379	1	B, C, D, E
d6732	12.004	11.439	302.282	302.157	-0.0135	-1.501	1	B, C, D, E
d6811	12.060	14.008	282.904	282.963	-0.0141	-4.310	3	A, B, C, D, E
d6812	12.072	14.565	298.348	298.489	-0.0125	-4.957	3	A, B, C, D, E
d6821	12.047	14.125	294.988	295.290	-0.0128	-2.015	1, 3	A, B, C, D, E
d6822	12.063	14.755	296.708	296.762	-0.0124	-3.406	1, 3	A, B, C, D, E
d6922	12.234	8.160	298.650	299.722	0.0092	-4.319	1, 2	A, B, C, D, E
d6931	12.220	7.631	300.870	301.563	0.0141	-12.204	1, 2	A, B, C, D, E
d6932	12.180	7.113	320.251	321.902	0.0133	-19.669	1, 2	A, B, C, D, E
d7011	12.050	7.813	284.392	285.735	0.0257	4.277	1	A, B, C, D, E
d7012	12.058	8.551	286.091	285.279	0.0141	-0.338		A, B, C, D, E
d7021	12.027	7.668	282.224	280.798	0.0216	-2.572		A, B, C, D, E
d7022	12.034	7.702	289.851	289.471	0.0120	0.931	1, 2	A, B, C, D, E
d7031	12.021	6.232	293.206	292.690	0.0098	-4.621	1, 2	A, B, C, D, E
d7032	12.026	6.355	289.984	289.838	0.0107	3.081		A, B, C, D, E
d7041	12.015	6.277	295.836	295.292	0.0119	2.272		A, B, C, D, E
d7042	12.030	7.358	284.200	283.058	0.0222	1.335		A, B, C, D, E
d7111	11.970	13.384	281.082	278.244	-0.0520	-3.600	1, 2, 3	A, C, D
d7112	12.083	13.597	290.102	288.744	-0.0305	-1.924	1, 2, 3	A, C, D
d7121	12.343	17.479	281.195	279.109	-0.0201	-3.743	1, 2, 3	C, D
d7131	12.249	15.686	278.623	276.417	-0.0078	-4.720	1, 2, 3	C, D

Table D.1. Phase II Data Index (concluded).

Campaign	Mean Blade 3 Pitch (deg)	Mean H.H. Wind Speed (m/s)	Mean North Wind Direction (deg)	Mean South Wind Direction (deg)	Mean Richardson Number	Mean Yaw Error Angle (deg)	Comments	Problems
d7132	12.346	17.038	274.915	272.786	-0.0039	-2.673	1, 2, 3	C, D
d7141	12.287	16.068	281.595	279.895	-0.0009	-2.009	1, 2, 3	C, D
d7142	12.480	18.879	282.556	281.314	-0.0010	-3.508	1, 2, 3	C, D
d7211	11.320	11.321	287.879	286.964	-0.0283	-5.849	1, 2, 3	C, D
d7212	11.459	14.519	270.537	268.331	-0.0173	-4.048	1, 2, 3	C, D
d7221	11.483	14.265	294.873	293.214	-0.0229	5.563	1, 2, 3	A, C, D
d7222	11.660	17.315	301.726	300.772	-0.0112	-3.837	1, 2, 3	A, C, D
d7231	11.417	13.566	294.625	293.765	-0.0231	1.023	1, 2, 3	C, D
d7232	11.239	10.333	279.209	276.422	-0.0154	-9.256	1, 2, 3	C, D
d7241	11.322	11.743	268.980	266.667	-0.0092	-5.291	1, 2, 3	A, C, D
d7242	11.188	8.453	280.712	278.135	-0.0013	-4.433	1, 2, 3	A, C, D
d7311	12.273	13.173	273.431	272.571	-0.1181	-3.895	2, 3	D, F, G
d7312	12.166	11.106	263.402	260.904	-0.1306	-6.011	1, 2	D, F, G
d7321	12.141	10.672	282.145	281.242	-0.1185	-2.503	2	A, D, F, G
d7322	12.019	7.866	285.360	282.120	-0.1034	-1.315	1, 2	A, D, F, G
d7331	11.986	6.974	301.370	300.655	-0.1856	-4.464	2	A, D, F, G
d7332	11.932	5.281	302.949	301.486	-0.4341	-8.763	2	A, D, F, G
d7341	11.927	5.719	317.689	316.323	-0.3442	3.278	2	A, D, F, G
d7342	11.915	4.979	327.890	319.569	-0.8427	3.906	1, 2	A, D, F, G
d7511	11.847	8.348	271.740	273.734	-0.1073	0.181	1, 2	
d7512	11.824	6.924	270.877	271.644	-0.2014	-1.924	1, 2	
d7521	12.918	7.433	284.093	283.957	-0.1556	-1.057	1, 2	
d7522	13.397	5.909	291.864	289.986	-0.1143	-3.909	1, 2	

Suite of Problems:

A. North met 5 m wind direction not working
B. North met 10 m wind direction not working
C. Sonic anemometer not working
D. Edge bending at 20% span not working
E. Torsion at 70% not working
F. Pressures did not work
G. Pressures at 80% did not work
H. Angle of attack flag at 63% did not work
I. Pitch angle improperly set

Suite of Comments:

1. PCM system lost sync momentarily
2. Locked yaw (in part or in full)
3. Contains an azimuth error

Table D.2. Phase III and Phase IV (1996) 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)	Comments	Problems	Calibration History
data1	2.370	7.642	7.884	302.268	300.756	303.965	-0.3083	4.318	2,5,10	F,G,H,I,L,M,N,O,Q,R,S,T	I, II
data2	1.700	8.447	8.138	264.575	263.711	263.414	0.0247	3.643	2,5,10	F,G,H,I,L,M,N,O,Q,R,S,T	II
data3	3.567	10.812	11.351	202.417	200.072	199.894	-0.1047	4.765	2,5,10	F,G,H,I,L,M,N,O,Q,T	II
data4	3.194	10.129	10.564	201.672	199.047	199.699	-0.1404	5.892	2,5,10	F,G,H,I,L,M,N,O,Q,T	II
parked1	62.427	14.971	17.957	286.838	285.405	287.759	-0.0172	-0.955	5,10	F,G,H,I,L,M,N,O,Q,T	II
parked2	71.137	15.060	17.619	285.770	283.776	286.011	-0.0310	-0.590	5,10	F,G,H,I,L,M,N,O,Q,T	II
slwrot2	68.091	14.666	18.275	293.275	292.640	294.073	-0.0284	-2.904	5,10	F,G,H,I,L,M,N,O,Q,T	II
slwrot3	65.241	19.529	23.213	275.096	273.805	266.976	-0.0342	-5.655	5,10	F,G,H,I,L,M,N,O,Q,T	II
data5	3.223	14.897	16.627	276.269	275.329	277.273	-0.0095	-6.397	2,5,10	F,G,H,I,L,M,N,O,Q,T	II
data6	2.511	12.479	15.566	288.307	287.035	289.426	-0.0310	-2.884	2,5,10	F,G,H,I,L,M,N,O,Q,T	II
data7	2.977	7.637	9.994	149.177	145.375	147.224	-0.2680	5.210	2,5	B,C,D,F,G,H,I,L,M,O,Q,T	II
data8	2.898	7.111	8.906	152.216	148.791	150.495	-0.6594	4.826	2,5	B,C,D,F,G,H,I,L,M,O,Q,T	II
data9	5.275	7.791	7.500	27.439	29.228	25.540	-0.0403	-90.844	2,5,9	B,C,D,F,G,H,I,J,L,M,O,Q,T	II, III
data10	6.044	11.818	11.408	23.225	22.033	23.846	-0.0388	-10.737	2,5	B,C,D,F,G,H,I,J,L,M,O,Q,T	II
data11	6.096	11.613	11.288	19.509	20.768	18.784	-0.1206	-8.409	2,5	B,C,D,F,G,H,I,J,L,M,O,Q,T	II
data12	5.638	12.639	12.648	67.448	106.588	37.682	-0.0684	-11.475	2,5	B,C,D,F,G,H,I,J,L,M,O,Q,T	II
data13	5.689	10.203	11.653	305.963	304.486	306.278	-0.0202	-4.041	2,5	B,C,D,F,G,H,I,J,L,M,O,Q,T	II
data14	5.459	7.001	7.183	308.881	307.376	309.821	-0.0310	-6.616	2,5	B,C,D,F,G,H,J,L,M,O,Q,T	II
data15	5.431	7.360	7.123	288.837	293.689	289.370	-0.0328	-11.773	2,5	B,C,D,F,G,H,J,L,M,O,Q,T	II
data16	2.616	8.218	7.903	336.718	334.962	339.488	-0.0192	-8.479	2,5	A,C,H,K,L,M,O,P,Q,T	II, IV
data17	2.512	10.304	10.063	347.992	345.857	340.464	-0.0470	-10.301	2,5	A,C,H,K,L,M,O,P,Q,T	II
data18	2.118	9.193	8.915	341.156	339.357	339.069	-0.0734	-10.139	2,5	A,C,H,K,L,M,O,P,Q,T	II
data19	2.595	6.094	5.769	327.518	326.353	330.581	-0.0589	-4.412	2,5	A,C,H,K,L,M,O,P,Q,T	II
data20	-0.875	3.460	2.932	135.608	132.041	137.112	-0.8303	35.166	2,4,9	E,J	I, II,V
data21	2.451	10.755	10.831	279.647	278.178	279.146	0.0451	-5.945	2,4	E,K	II,V
data22	2.423	11.802	11.831	278.941	277.361	278.388	0.0385	-5.576	2,4	E	II,V
data23	2.948	13.126	13.243	283.375	282.362	282.988	0.0268	-5.836	2,4	E	II,V
data24	3.390	15.129	15.459	283.395	281.820	283.051	0.0192	-8.314	2,4	E	II,V
data25	3.899	15.758	15.989	280.300	278.923	279.933	0.0158	-5.659	2,4	E	II,V
data26	3.926	15.695	15.853	277.942	276.470	277.452	0.0170	-8.239	2,4	E	II,V
data27	3.575	13.416	13.421	274.634	272.977	274.072	0.0253	-3.579	2,4	E	II,V
data28	4.883	13.140	13.094	269.480	268.119	269.011	0.0264	-5.208	2,4	E,J	II,V
data29	2.616	12.951	12.866	270.335	269.213	269.866	0.0300	-3.334	2,4	E	II,V
data30	3.128	14.287	14.309	275.568	274.625	275.245	0.0203	-7.114	2,4	E	II,V
data31	2.626	10.599	10.358	260.712	259.526	259.743	0.0345	-2.335	2,4	E	II,V
data32	2.814	13.251	12.947	260.224	258.874	259.175	0.0188	-3.131	2,4	E	II,V
data33	2.875	12.718	12.537	258.675	257.134	257.588	0.0321	-2.656	2,4	E	II,V
data34	2.218	10.671	10.431	252.585	250.939	251.171	0.0558	-0.575	2,4	E	II,V
data35	2.524	7.061	6.891	255.705	254.117	254.430	0.1712	2.925	2,4	E	II,V

Table D.2. Phase III and Phase IV (1996) 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)	Comments	Problems	Calibration History
data36	2.290	6.639	6.452	261.728	260.038	260.433	0.1893	0.753	2, 4	E	II, V
data37	2.691	6.941	6.829	283.561	282.816	283.026	0.1564	-5.642	2, 4	E	II, V
data38	2.530	6.162	6.069	295.576	294.487	294.819	-0.1231	-4.255	2, 4	E	II, V
data39	2.796	13.894	14.415	282.957	281.643	282.554	0.0081	-7.404	2, 4	E	II, V
data40	3.030	11.182	11.276	289.996	288.739	289.442	0.0076	-4.345	2, 4	E	II, V
data41	3.014	10.875	10.891	293.017	291.787	292.696	0.0083	-4.749	2, 4	E	II, V
data42	2.924	9.074	9.190	315.991	314.300	316.114	-0.0349	-3.472	2, 4	E	II, V
data43	2.877	8.642	8.688	303.574	302.323	303.633	-0.1286	-4.584	2, 4	E	II, V
data44	2.890	7.386	7.239	261.192	260.268	260.037	-0.1775	5.365	2, 4	E	II, V
data45	2.982	9.022	8.883	268.994	267.512	267.993	-0.0927	-4.407	2, 4	E	II, V
data46	3.005	9.611	9.603	276.809	275.197	275.983	-0.1148	-6.470	2, 4	E	II, V
data47	3.152	10.815	10.800	273.411	272.531	272.737	-0.0936	-4.000	2, 4	E	II, V
data48	2.942	8.152	8.121	294.061	293.145	293.997	-0.1259	-2.769	2, 4	E	II, V
data49	2.936	7.313	7.270	302.177	301.182	302.288	-0.1567	-1.640	2, 4	E	II, V
data50	2.969	6.720	6.670	283.773	283.101	282.967	-0.1532	-4.737	2, 4	E	II, V
data51	2.299	5.616	5.478	291.818	290.147	290.904	-0.2539	-65.535	2, 4, 9	E	II, V
data52	3.254	10.429	10.543	286.044	285.344	285.700	-0.0480	-7.036	2, 4	E	II, V
data53	3.236	9.845	9.786	284.584	282.984	283.876	-0.0814	-3.483	2, 4	E	II, V
data54	3.485	11.343	11.255	267.032	266.023	266.209	-0.0747	-2.994	2, 4	E	II, V
data55	3.322	9.860	9.861	275.807	274.483	274.771	-0.1379	-5.627	2, 4	E	II, V
data56	3.428	10.890	10.849	281.765	280.848	281.193	-0.1044	-3.730	2, 4	E	II, V
data57	-3.331	11.386	11.394	288.888	287.686	288.649	-0.0812	-6.270	1, 4	E	II, V
data58	-3.352	10.594	10.586	289.181	288.278	288.690	-0.1105	-6.711	1, 4	E	II, V
data59	-3.466	9.149	9.170	296.916	296.095	296.947	-0.1747	-4.935	1, 4	E	II, V
data60	7.238	7.683	7.638	294.594	293.261	294.243	-0.3481	12.346	3, 4, 9	E	II, V
data61	7.921	9.391	9.261	258.078	256.142	256.792	-0.0515	1.942	3, 4	E	II, V
data62	7.991	10.924	10.748	248.284	246.991	246.467	-0.0577	0.183	3, 4	E	II, V
data63	7.996	11.589	11.361	244.490	242.744	242.031	-0.0329	-0.512	3, 4	E	II, V
data64	8.000	8.844	8.626	245.693	244.116	243.606	-0.0444	-3.070	3, 4	E	II, V
data65	-2.747	9.786	9.559	239.055	237.563	236.710	-0.1009	0.801	1, 4	E	II, V
data66	-2.648	10.360	10.188	234.052	232.538	231.187	-0.0630	0.681	1, 4	E	II, V
data67	-2.849	8.537	8.396	250.278	249.262	248.684	-0.1758	-0.742	1, 4	E	II, V
data69	7.840	13.403	13.182	251.076	249.618	248.986	-0.0917	-2.040	1, 4	E	II, V
data70	7.531	11.206	11.177	270.370	269.492	269.623	-0.1468	-3.124	3, 4	E	II, V
data71	2.622	7.289	7.090	249.942	248.843	248.383	-0.4219	-9.172	3, 4, 6	E	II, V
data72	3.772	10.112	9.903	250.493	249.569	249.033	-0.2063	9.309	2, 4, 6	E	II, V
data73	3.557	7.210	6.938	238.213	235.897	235.444	-0.6046	39.644	2, 4, 6	E	II, V
data74	2.845	9.045	8.843	233.717	232.639	231.270	-0.2534	-3.647	2, 4, 6	E	II, V
data75	2.957	10.477	10.327	230.087	228.428	227.253	-0.2813	-4.606	2, 4, 6	E	II, V
data76	-2.304	10.704	10.440	237.314	236.158	234.934	-0.2131	1.745	2, 4, 6, 8	E	II, V

Table D.2. Phase III and Phase IV (1996) 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)	Comments	Problems	Calibration History
data77	-0.716	10.778	10.611	235.591	233.883	232.873	-0.2257	3.263	2, 4, 6, 8	E	II, V
data78	2.790	10.020	9.841	251.596	250.142	249.928	-0.2706	-37.979	2, 4, 6	E	II, V
data79	2.899	8.559	8.289	236.847	235.149	234.452	-0.3269	20.368	2, 4, 6	E	II, V
data80	2.868	8.832	8.624	235.299	232.760	232.745	-0.1354	42.049	2, 4, 6	E	II, V
data81	2.880	19.867	20.050	271.538	270.110	271.042	0.0085	-9.359	2, 4	E	II, V, VI
data82	2.675	16.618	16.794	273.427	272.110	273.181	0.0146	-5.134	2, 4	E	II, V
data83	2.902	17.520	17.624	267.794	266.455	267.168	0.0142	-5.085	2, 4	E	II, V
data84	3.036	15.531	15.424	261.029	259.921	260.125	0.0217	-3.952	2, 4	E	II, V
data85	3.704	16.021	15.862	251.117	249.663	249.336	0.0196	-3.426	2, 4	E	II, V
data86	2.649	15.172	15.068	254.151	253.010	252.644	0.0215	-4.686	2, 4	E	II, V
data87	2.742	11.776	11.685	252.008	250.830	250.460	0.0444	-1.627	2, 4	E	II, V
data88	2.888	9.311	9.163	246.307	244.607	244.457	0.0881	2.043	2, 4	E	II, V
data89	2.729	8.231	8.053	239.219	237.094	236.706	0.1239	2.628	2, 4	E	II, V
data90	3.375	13.374	13.887	285.385	283.946	284.633	-0.0216	-4.046	2, 4	E	II, V
data91	2.501	13.974	14.357	294.896	293.533	294.550	-0.0417	-1.719	2, 4, 7	E	II, V
data92	2.763	14.203	14.582	296.046	294.750	295.984	-0.0427	-3.759	2, 4	E	II, V
data93	2.923	12.027	12.172	309.732	308.143	310.116	-0.0663	-1.034	2, 4	E	II, V
data94	2.355	9.203	9.135	297.663	297.392	295.732	-0.1134	-4.873	2, 4, 9	E	II, V
data95	2.480	8.266	8.196	293.166	292.482	292.669	-0.1520	-2.048	2, 4	E	II, V
slwrot4	68.619	15.111	15.488	276.995	275.941	276.191	-0.5234	-0.186	4	E	II, V
slwrot5	68.899	15.537	16.290	290.896	289.621	290.465	-0.4645	-0.943	4	E	II, V
data96	3.114	13.901	14.237	290.687	290.199	290.972	-0.0656	-11.426	2, 4	E	II, V
data97	2.851	15.072	15.308	288.725	287.459	288.306	-0.0592	-5.136	2, 4, 7	E	II, V
data98	2.962	13.787	14.052	291.774	290.854	291.742	-0.0614	-5.258	2, 4	E	II, V
data99	3.353	16.391	16.420	275.937	274.247	274.939	-0.0485	-4.733	2, 4	E	II, V
data100	2.711	7.547	7.509	282.782	280.922	281.827	0.1030	-4.890	2, 4	E	II, V
data101	2.663	7.578	7.601	290.084	288.746	289.532	0.0208	-5.964	2, 4	E	II, V
data102	3.047	6.462	6.398	295.653	294.406	295.338	0.0440	-4.759	2, 4	E	II, V
data103	2.927	9.137	9.041	234.639	232.705	231.926	-0.0886	2.934	2, 4	E	II, V
data104	2.842	6.856	6.723	233.934	231.622	231.375	-0.1223	8.789	2, 4	E	II, V
data105	2.822	8.178	8.061	240.338	238.727	238.238	-0.1752	4.195	2, 4	E	II, V
data106	2.846	7.921	7.824	241.754	240.091	239.684	-0.1532	1.654	2, 4	E	II, V
data107	2.736	4.768	4.555	259.890	258.081	258.594	-0.2507	13.640	2, 4, 9	E	II, V
data108	2.553	4.474	4.446	243.718	241.034	242.556	-0.0310	28.486	2, 4, 9	E	II, V
data109	2.317	7.612	7.317	231.677	229.864	229.180	-0.2791	-0.732	2, 4, 9	E	II, V
data110	2.736	7.428	7.211	240.156	238.706	238.337	-0.4089	4.079	2, 4, 9	E	II, V
data111	2.593	9.085	9.008	289.425	287.183	288.637	-0.2118	-13.734	2, 4	E	II, V
data112	2.873	9.164	9.005	280.945	279.496	280.321	-0.1982	-5.494	2, 4	E	II, V

Table D.2. Phase III and Phase IV (1996) Data Index (concluded)

Suite of problems:

A. All blade tip accelerometers out
B. Blade 1 flap accelerometer out
C. Blade 1 strain gauges out
D. Blade 2 pitch is different than the pitch of the other blades
E. Blade 3 25% and 60% gauges out
F. Nacelle accelerometers filtered at 10Hz instead of 100Hz
G. Nacelle had no fore-aft sway accelerometer
H. North met wind elevation drifts (zero point changes)
I. 5-hole probe at 91% is rotated and therefore not accurate
J. Pitch angle improperly set
K. Pressures did not work
L. Rotor out of balance
M. Sonic anemometer occasionally glitches
N. Taps 11/92 and 18/92 not hooked up
O. Yaw position has about 3° of hysteresis
P. Blade 3 25% gauges out
Q. Barometric pressure railed at 80kPa
R. Blade 3 flap acceleration positive upwind
S. Nacelle pitch accelerometer cal. coefficients incorrect
T. No yaw moment gauge

Calibration history:

I. Full system calibration (all non-pressure channels)
II. Pressure channel calibration before and after data collection
III. Yaw angle and blade pitch angle offset calibrations
IV. Nacelle accelerometers electronics calibrations
V. Blade 1 flap, blade 3 flap and edge accelerometer sensitivities not updated in calconst.xls
VI. Zero offset determination for blade root gages, LSS bending and torque gages.

Suite of comments:

1. -3° pitch
2. 3° pitch
3. 8° pitch
4. 5-hole probes used at all stations
5. Angle of attack flags are used at 30%, 47%, 63%, 80%
6. Locked yaw (in part or in full)
7. Pitch angle adjusted during run
8. Pitch sweeps
9. Turned up-wind during run
10. Temperature sensor used instead of delta-T

Table D.3. Phase III and Phase IV (1996) Cycles Corrupted by Heater

Disk	Cycles Corrupted by Heater
parked2	all
slwrot2	345-725
slwrot3	0-131, 540-725
data2	203-532
data4	181-476
data5	347-650
data6	168-472
data7	219-526
data8	353-670
data9	0-106, 523-725
data10	424-725
data11	104-443
data12	0-116, 570-725
data13	454-725
data14	449-725
data15	280-600
data18	52-362
data20	409-684
data21	Pressures not working
data22	0-295
data23	80-430
data24	260-555
data25	235-555
data26	190-500
data27	200-486

Disk	Cycles Corrupted by Heater
data28	206-500
data29	204-500
data30	159-436
data31	114-405
data32	130-410
data33	42-330
data34	0-195
data35	0-150
data36	0-105
data37	0-64
data39	0-330
data40	138-455
data41	0-239
data44	488-725
data45	464-725
data46	468-725
data47	374-671
data48	367-679*
data49	364-673
data50	406-725
data51	301-725
data52	0-320
data53	440-725
data54	104-405
data55	0-213

Disk	Cycles Corrupted by Heater
data57	500-725*
data58	314-633
data59	228-521
data60	185-489
data62	279-567
data63	416-725
data64	595-725
data66	0-130
data67	66-350
data69	494-725
data72	77-440
data75	209-490
data76	515-725
data80	578-725
data90	107-450
data91	197-514
data92	0-124, 550-725
data93	132-440
data94	0-71, 615-725*
data95	185-510
data97	0-137*
data107	302-725
data108	0-105, 515-725
data110	670-725
slwrot4	350-725
slwrot5	0-375

* Because the turbine yawed upwind the heaters may not have caused the pressure offset.

Table D.4. Phase IV (1997) Data Index

Run Order	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)	Comments	Problems	Calibration History
1	d403001	2.477	22.483	24.271	279.575	279.319	276.185	-0.0200	-16.404	2, 6, 7, 8		I, II
2	d403002	2.296	20.001	19.729	266.654	265.812	265.425	-0.0236	-5.368	2, 8		II, IV, V
3	d408001	7.871	19.538	19.159	264.265	264.034	262.980	-0.0161	-6.822	3, 8	A	III
4	d403003	2.878	19.640	19.663	270.644	270.397	269.796	-0.0296	-13.130	2, 8		III
5	d408002	8.008	19.830	19.638	266.689	266.520	265.562	-0.0319	-8.577	3, 8		III
6	d403004	2.916	19.064	18.836	268.162	267.942	267.121	-0.0316	-12.758	2, 8		III
7	d4m3001	-3.179	15.504	15.270	262.870	262.448	261.333	-0.0605	-4.181	1, 8, 9		III
8	d4m3002	-2.852	17.582	17.571	272.197	271.925	271.380	-0.0372	-3.913	1, 8		III
9	d403005	2.880	16.413	16.273	270.236	269.886	269.376	-0.0153	-4.936	2, 8, 10		III
10	d403006	3.365	14.930	14.611	252.849	252.146	250.684	-0.0406	-5.025	2, 8		III
11	d4pb001	69.512	14.363	14.122	267.315	266.352	265.982	-0.0563	14.412	6, 8, 11, 13		III
12	d4pb002	69.716	14.260	14.299	272.067	271.312	270.880	-0.0613	-8.805	8, 11, 13		III
13	d4sr001	64.370	14.984	15.488	284.210	283.325	283.595	-0.0124	-2.607	8		II
14	d4pb003	68.508	11.309	11.433	300.761	300.385	300.990	-0.0906	-8.194	12		II
15	d403007	3.148	11.245	11.391	307.695	309.184	307.613	-0.0611	-17.448	2, 6		II
16	d403008	2.884	8.510	8.457	302.315	302.244	302.974	-0.1304	-7.457	2	A	III
17	d403009	2.660	8.624	8.545	285.194	285.009	284.604	0.0618	-8.113	2		II
18	d403010	2.901	10.370	10.318	281.982	281.359	280.894	-0.2101	-5.861	2		II, IV
19	d403011	2.666	8.726	8.557	288.154	287.074	287.596	-0.2515	-4.869	2		II, V
20	d403012	2.945	10.439	10.483	290.813	290.536	290.365	-0.2026	-5.973	2, 6		III
21	d4m3003	-2.834	9.223	9.019	288.003	287.267	287.493	-0.3156	-2.181	1		III
22	d4m3004	-3.028	8.335	8.141	276.185	275.756	274.962	-0.4078	-1.210	1		III
23	d408003	7.667	8.485	8.399	289.535	289.045	289.097	-0.3568	-14.161	3		II
24	d408004	6.730	7.475	7.483	302.460	302.276	302.929	-0.4878	-51.460	3, 6, 14		III
25	d403013	2.474	5.919	5.801	301.296	301.192	302.058	-0.6654	-36.398	2, 9, 14		II
26	d403014	2.932	4.957	4.843	318.739	321.384	320.408	-0.6279	-4.986	2, 10		III
27	d403015	2.263	10.020	10.009	276.542	276.031	275.219	-0.0083	-5.871	2		II
28	d403016	2.220	9.714	9.480	265.594	264.727	264.135	0.0059	-3.289	2		III
29	d403017	2.038	7.183	6.948	270.175	269.270	269.030	0.0269	-3.269	2		III
30	d403018	3.299	12.115	12.448	293.675	293.565	293.695	-0.0464	-6.186	2, 6		II
31	d4pb004	67.979	10.088	10.019	318.113	317.094	318.502	-0.0590	-5.972	11		II
32	d403019	1.829	6.337	6.094	310.456	310.953	311.085	-0.1718	-88.448	2, 7, 14		II
33	d403020	3.135	9.862	9.728	298.633	300.360	296.631	-0.0725	-12.490	2		III
34	d403021	2.202	6.528	6.297	285.629	292.239	283.673	-0.1412	2.978	2, 14		III
35	d403022	2.293	10.122	10.184	302.234	303.194	303.676	-0.0179	-11.501	2, 10		II
36	d403023	2.549	5.803	5.618	273.011	281.590	271.844	-0.0541	-0.872	2, 14		III

Table D.4. Phase IV (1997) Data Index (continued)

Run Order	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)	Comments	Problems	Calibration History
37	d403024	2.848	9.394	9.307	277.782	278.003	276.892	-0.1488	-4.718	2		II
38	d4m3005	-3.438	8.226	8.037	289.353	288.302	288.551	-0.2165	-3.732	1, 10		III
39	d4m3006	-3.043	10.291	10.405	281.807	281.433	280.984	-0.2420	-6.105	1		III
40	d408005	7.502	9.788	9.917	294.326	294.091	294.275	-0.2029	-10.469	3		III
41	d408006	7.640	11.933	11.716	260.798	260.587	259.088	-0.1513	-4.135	3		III
42	d403025	2.635	8.506	8.421	288.460	288.387	288.474	-0.3212	-5.900	2, 9		II
43	d403026	2.997	10.440	10.535	307.838	307.849	308.409	-0.1645	-7.922	2		III
44	d403027	3.290	10.685	10.831	295.656	296.074	296.021	-0.1447	-8.503	2		III
45	d403028	3.042	12.839	13.350	293.133	293.195	293.367	-0.0995	-6.074	2		III
46	d403029	2.594	10.459	10.262	282.615	282.042	281.790	-0.1333	-2.431	2		III
47	d403030	1.768	7.629	7.471	255.635	255.194	253.567	-0.2922	1.317	2, 6, 10		III
48	d403031	3.033	9.690	9.738	280.481	279.665	279.880	-0.1457	-15.747	2, 6, 14		III
49	d403032	2.196	9.132	9.165	278.804	278.336	277.758	-0.1606	-3.833	2, 15		III
50	d403033	2.810	10.426	10.494	304.246	305.057	305.146	-0.1540	-7.621	2, 10		III
51	d403034	2.345	7.748	7.665	304.677	306.136	302.800	-0.1977	-22.813	2, 14		III
52	d403035	2.940	10.882	11.011	287.976	288.222	287.723	-0.0919	-6.137	2		III
53	d403036	2.717	10.660	10.707	282.702	282.421	281.949	-0.0735	-4.772	2		III
54	d4pb005	69.689	11.774	11.676	272.778	272.682	271.516	-0.0240	-0.271	6, 10, 11		II
55	d4pb006	67.762	10.233	10.217	284.298	283.731	283.468	-0.0100	22.444	6, 11		II, VII
56	d4pb007	67.805	9.543	9.467	289.329	289.579	289.468	-0.0040	-2.453	11		II
57	d408007	7.391	11.255	11.448	286.891	286.490	286.434	0.0084	-8.229	3		II
58	d408008	7.667	12.992	13.462	289.679	288.832	289.267	0.0093	-6.783	3, 10		III, VII
59	d408009	7.562	12.827	13.013	281.799	281.200	280.743	0.0132	-6.547	3		II
60	d408010	7.619	12.682	12.904	278.960	278.402	277.864	0.0172	-5.264	3, 10		III
61	d408011	7.938	14.250	14.743	284.569	283.968	284.024	0.0111	-6.740	3	B	III
62	d408012	8.195	16.503	17.930	287.575	287.154	287.190	0.0080	-6.603	3, 10	B	II
63	d403037	2.968	17.669	18.024	277.701	277.262	276.622	0.0075	-9.443	2	B	III
64	d403038	3.308	13.232	13.842	292.083	291.612	291.974	0.0067	-8.454	2		II, VI
65	d403039	3.660	12.912	13.242	294.864	294.269	295.150	0.0107	-6.725	2, 9	C	III
66	d4pb008	57.314	13.922	14.447	287.522	287.449	287.330	0.0041	-5.607	6, 11, 13, 15		II
67	d4pb009	57.239	11.827	12.070	294.881	294.351	295.059	0.0015	-10.425	11, 13		II
68	d4m3007	-3.233	10.288	10.365	302.662	302.186	303.096	0.0011	-6.996	1		II
69	d4m3008	-3.027	10.843	10.948	307.156	306.921	307.850	0.0030	-9.952	1		III
70	d4m3009	-3.751	7.810	7.848	317.968	317.733	318.983	0.0029	-5.244	1		III
71	d4m3010	-2.393	9.674	9.770	295.763	295.494	295.812	-0.1903	-8.561	1		II
72	d4m3011	-2.696	8.348	8.469	309.776	309.855	310.889	-0.3161	-5.715	1, 6		III

Table D.4. Phase IV (1997) Data Index (concluded)

Run Order	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)	Comments	Problems	Calibration History
73	d4m3012	-2.763	8.770	8.801	300.232	300.490	300.655	-0.2407	-7.421	1		III
74	d4m9001	-8.933	7.656	7.623	305.252	305.410	305.967	-0.0073	-5.246	4		III
75	d412001	11.683	7.244	7.262	300.723	300.283	301.154	-0.0075	-52.581	5, 7, 14		III

Suite of problems:

A. Possible precipitation
B. Possible analog channel glitches (B1RFB, LSSTQ)
C. Possible pressure error

Suite of comments:

1. -3° pitch
2. 3° pitch
3. 8° pitch
4. -9° pitch
5. 12° pitch
6. Door opened
7. Cell phone in operation
8. Modal test ring on tower
9. Pressure taps purged prior to acquisition
10. Air conditioner cycled on
11. Parked instrumented blade at 0° azimuth
12. Parked instrumented blade at 180° azimuth
13. Locked yaw (in part or in full)
14. Turned up-wind during run
15. Pitch angle adjusted during run

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 channel
IV. Wind speed signal conditioner calibration verified
V. Temperature, wind elevation and direction signal conditioners calibration verified
VI. Pitch system cal.
VII. Pressure calibration failed; reboot Mensor; use next pre-cal as post-cal.

Note: Root edge bending moment is positive in the opposite direction of rotation throughout Phase III and Phase IV.
The electric heater in the rotating instrumentation package caused the reference pressure to fluctuate slightly throughout Phase III and Phase IVa.
Night video

Appendix E

Phase II Azimuth Errors

Phase II Azimuth Errors

The following table lists the various azimuth errors that have occurred in the Phase II Unsteady Aerodynamics Experiment data. These errors were caused by the saw-tooth wave applied to the azimuth encoder channel. The errors caused two adjacent cycles to be labeled as a single cycle. Instead of a single cycle containing 0.83 seconds of data, it has 1.67 seconds of data. This condition can easily cause a variety of problems; thus, it is important to know which campaigns contain these errors. This table lists the campaigns that have errors and then indicates errors by stating the first of two rotational cycles the data processing has turned into a single cycle. The first cycle of each campaign contains only half a rotational cycle which was labeled cycle 0. If researchers are using the program *scrunch.for* to extract the data, the program is able to identify these errors.

Campaign	Azimuth Errors (Cycle numbers)
D6611	90, 151, 153, 286
D6811	85, 87, 221, 223
D6812	138, 227, 229, 333, 335
D6821	111, 113, 208, 210, 218, 320
D6822	134, 136, 224, 226, 315, 317, 397
D7111	189
D7112	177, 179
D7121	122, 207, 282, 356
D7131	75, 77, 152, 248, 250
D7132	84, 149, 216, 334
D7141	81, 83, 163, 165, 241, 351
D7142	68, 135, 203, 205, 263, 334, 336
D7211	227, 229, 231
D7212	212, 283, 285
D7221	111, 183, 185, 297
D7222	95, 97, 168, 170, 241, 329
D7231	92, 94, 253, 255, 295
D7232	156
D7241	216
D7242	31
D7311	138

Appendix F

Additional Drawings

Figure F.1. Plan View of Site Layout

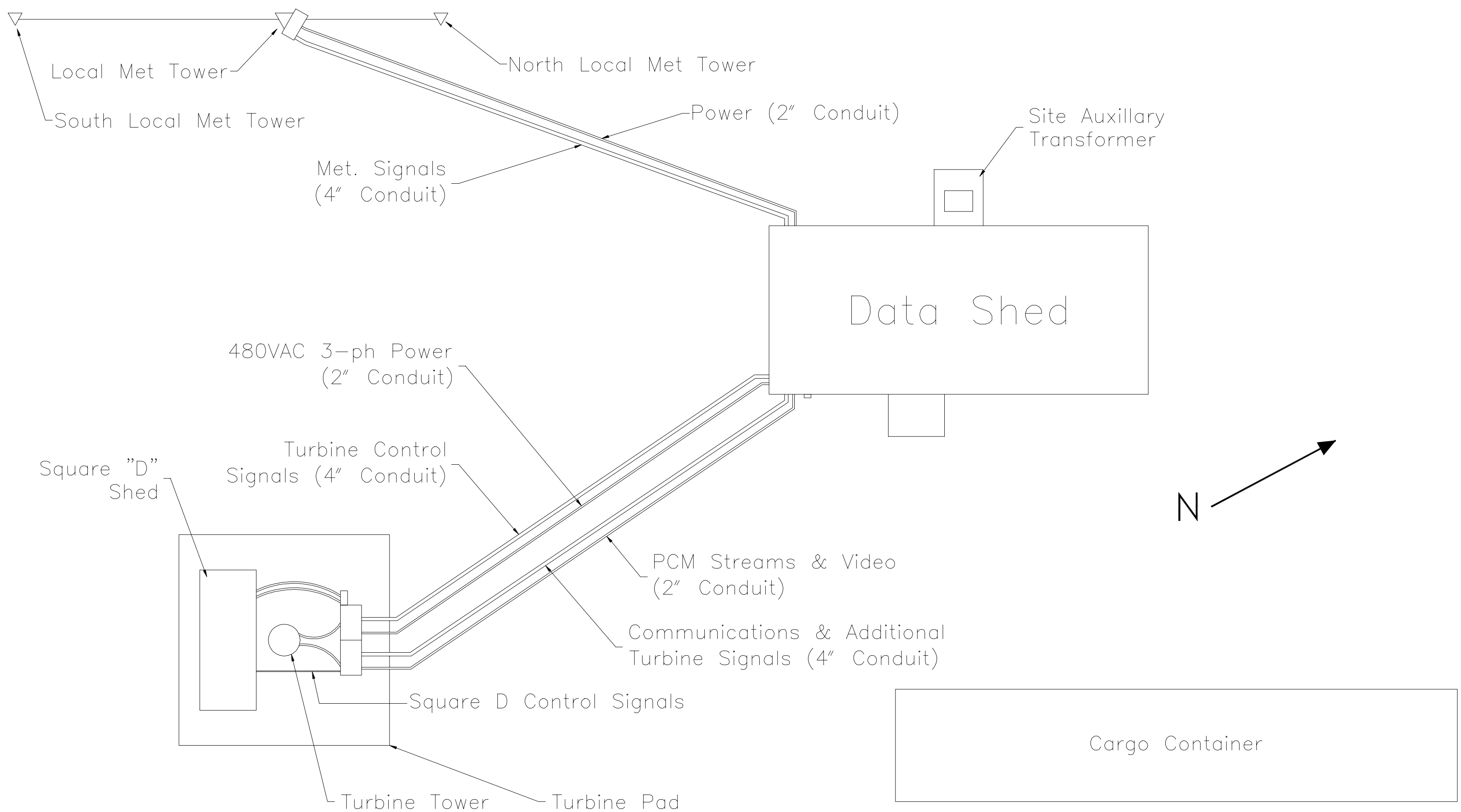


Figure F.2. Plan View of Site Showing Location of Meteorological Instruments Relative to Turbine

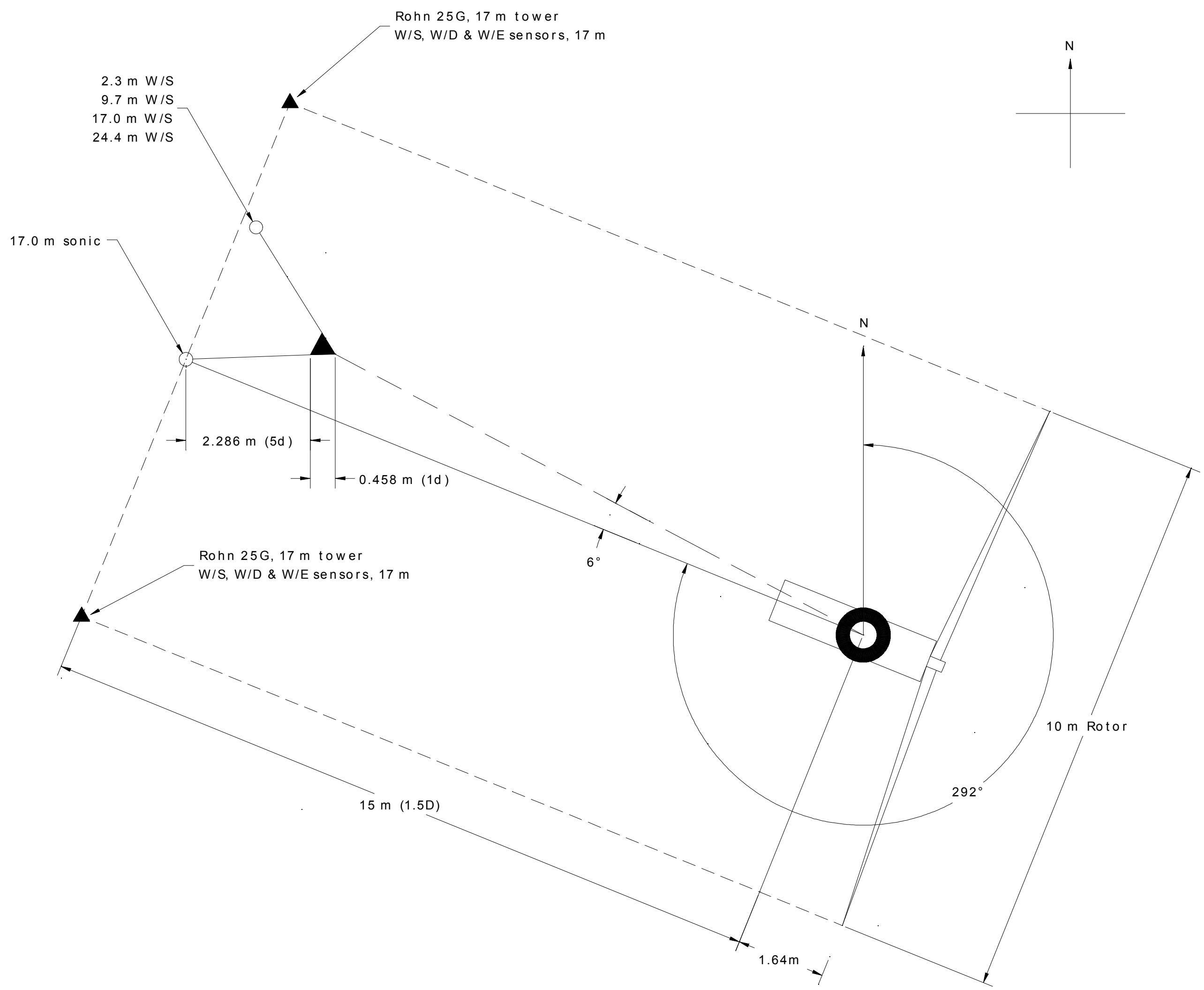


Figure F.3. Rotor Instrumentation Block Diagram

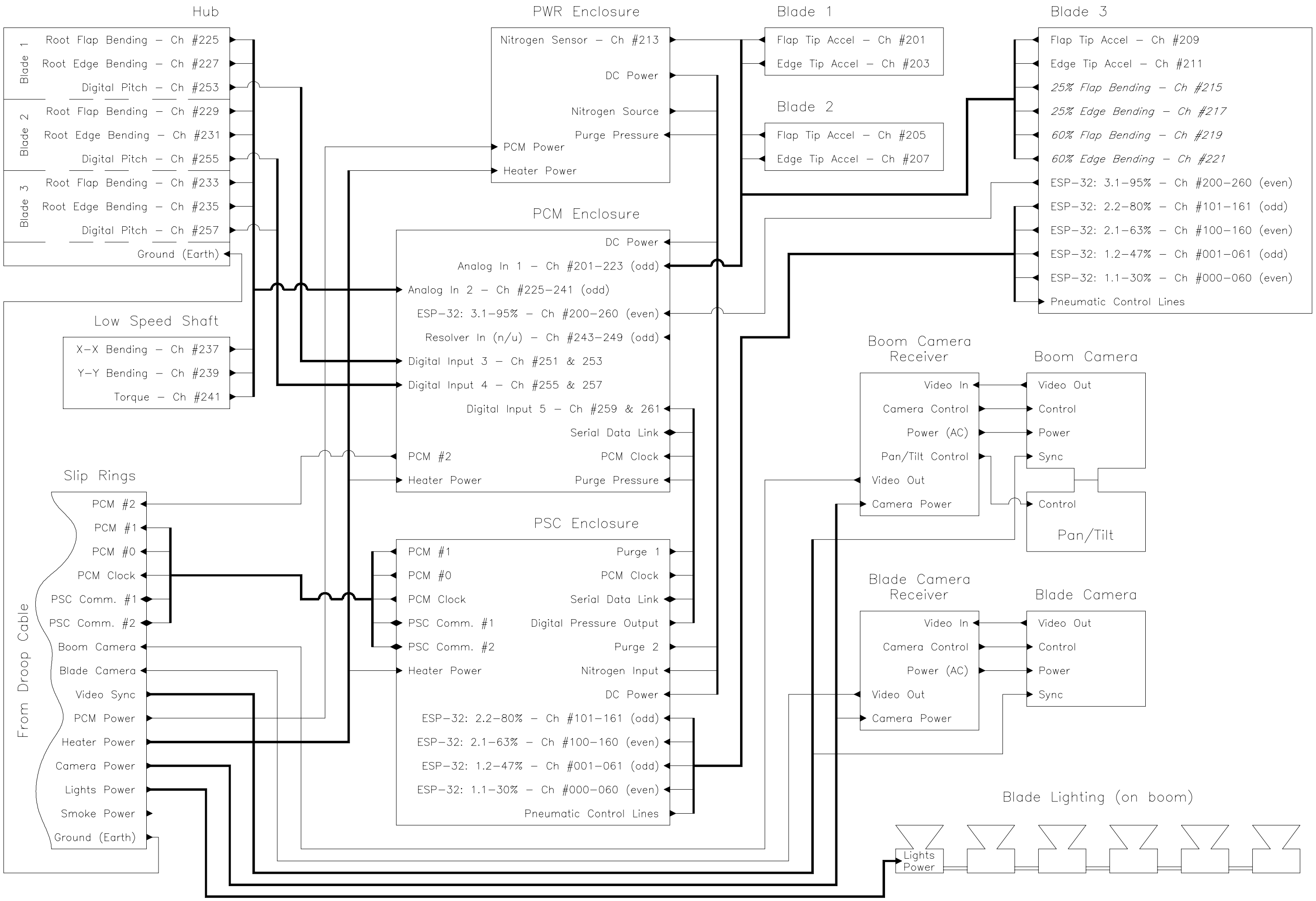


Figure F.4. Rotor Instrumentation Enclosure and Connector Layout

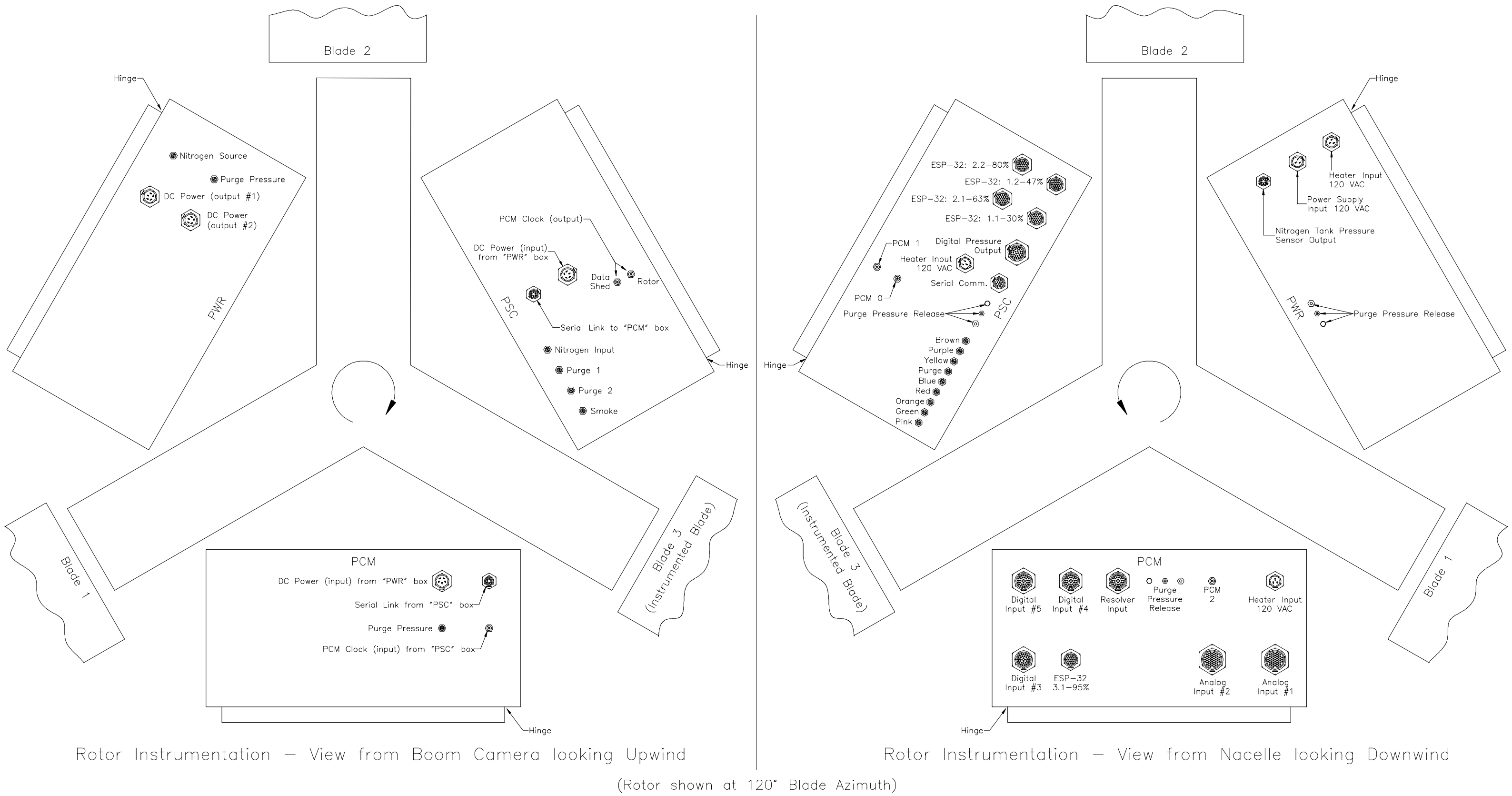
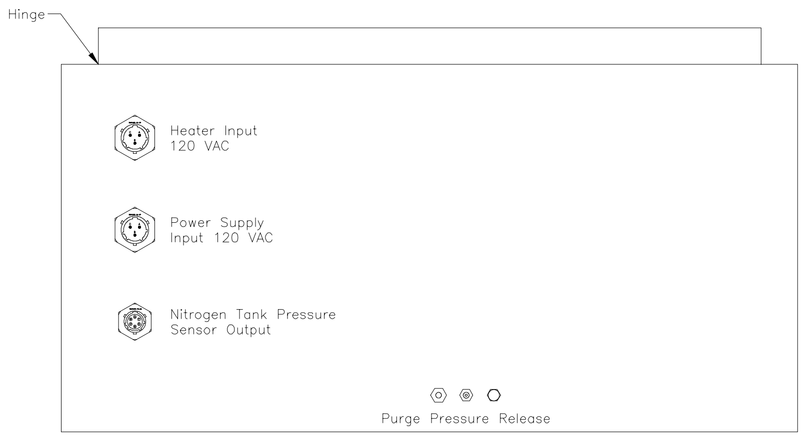
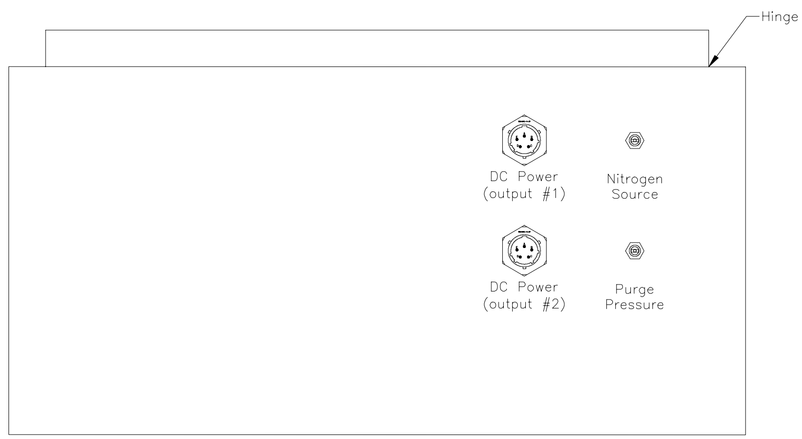


Figure F.5. Rotor-based PWR Enclosure (side view)

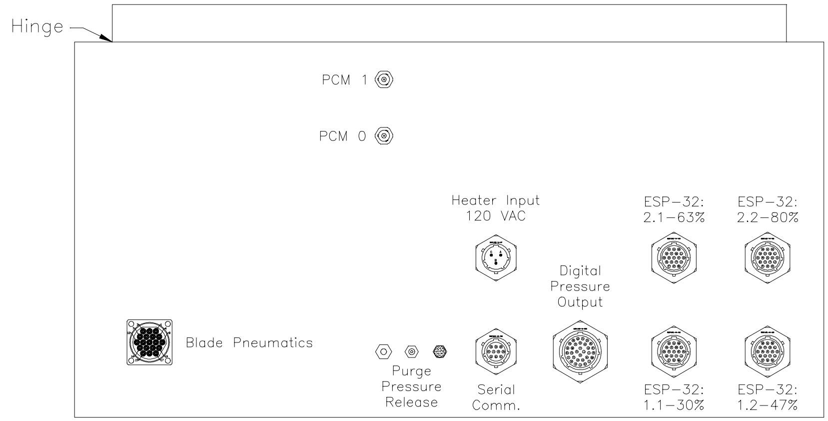


PWR Enclosure – View from Nacelle looking Downwind

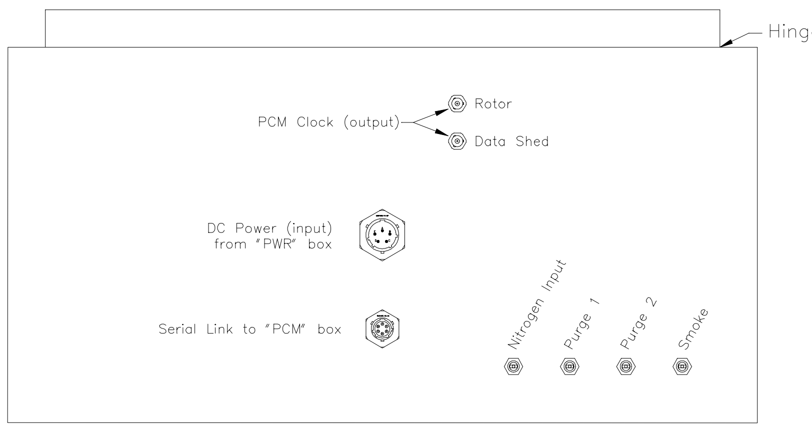


PWR Enclosure – View from Boom Camera looking Upwind

Figure F.6. Rotor-based PSC Enclosure (side view)



PSC Enclosure – View from Nacelle looking Downwind



PSC Enclosure – View from Boom Camera looking Upwind

Figure F.7. Rotor-based PSC Enclosure (Top View)

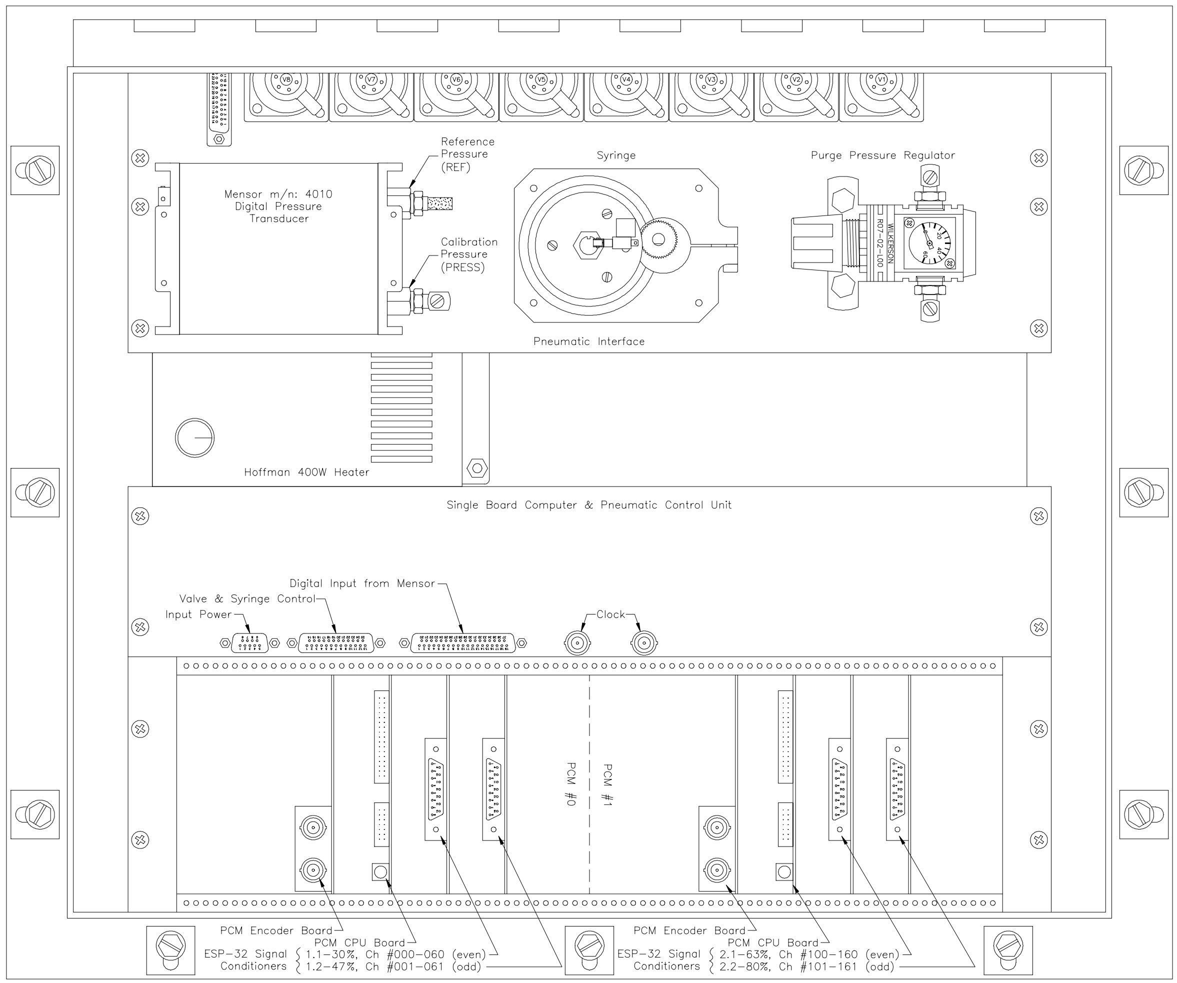
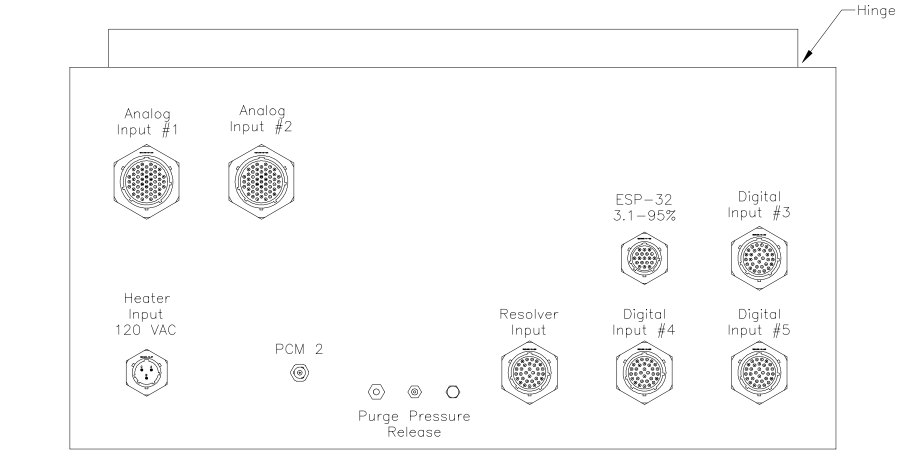
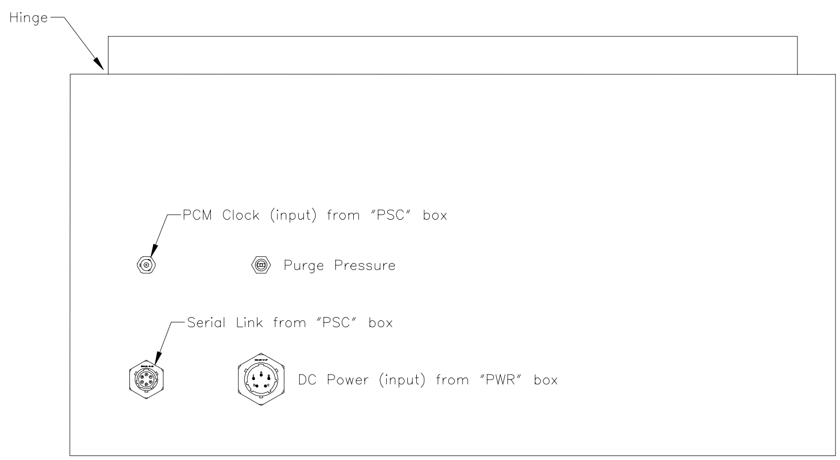


Figure F.8. Rotor-based PCM Enclosure (Side View)



PCM Enclosure – View from Nacelle looking Downwind



PCM Enclosure – View from Boom Camera looking Upwind

Figure F.9. Ground-based PCM Rack Power

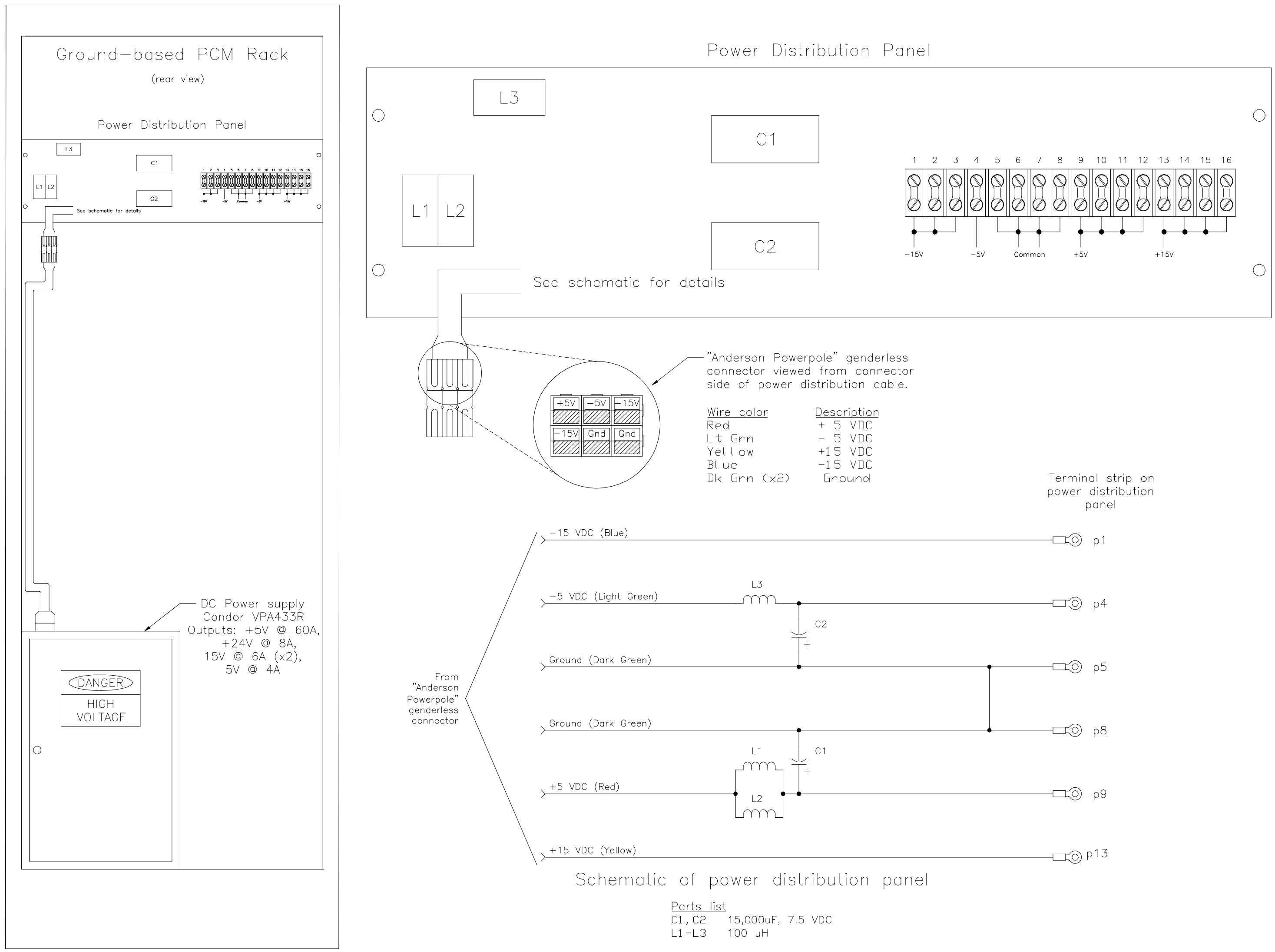


Figure F.10. Ground-based PCM rack I/O

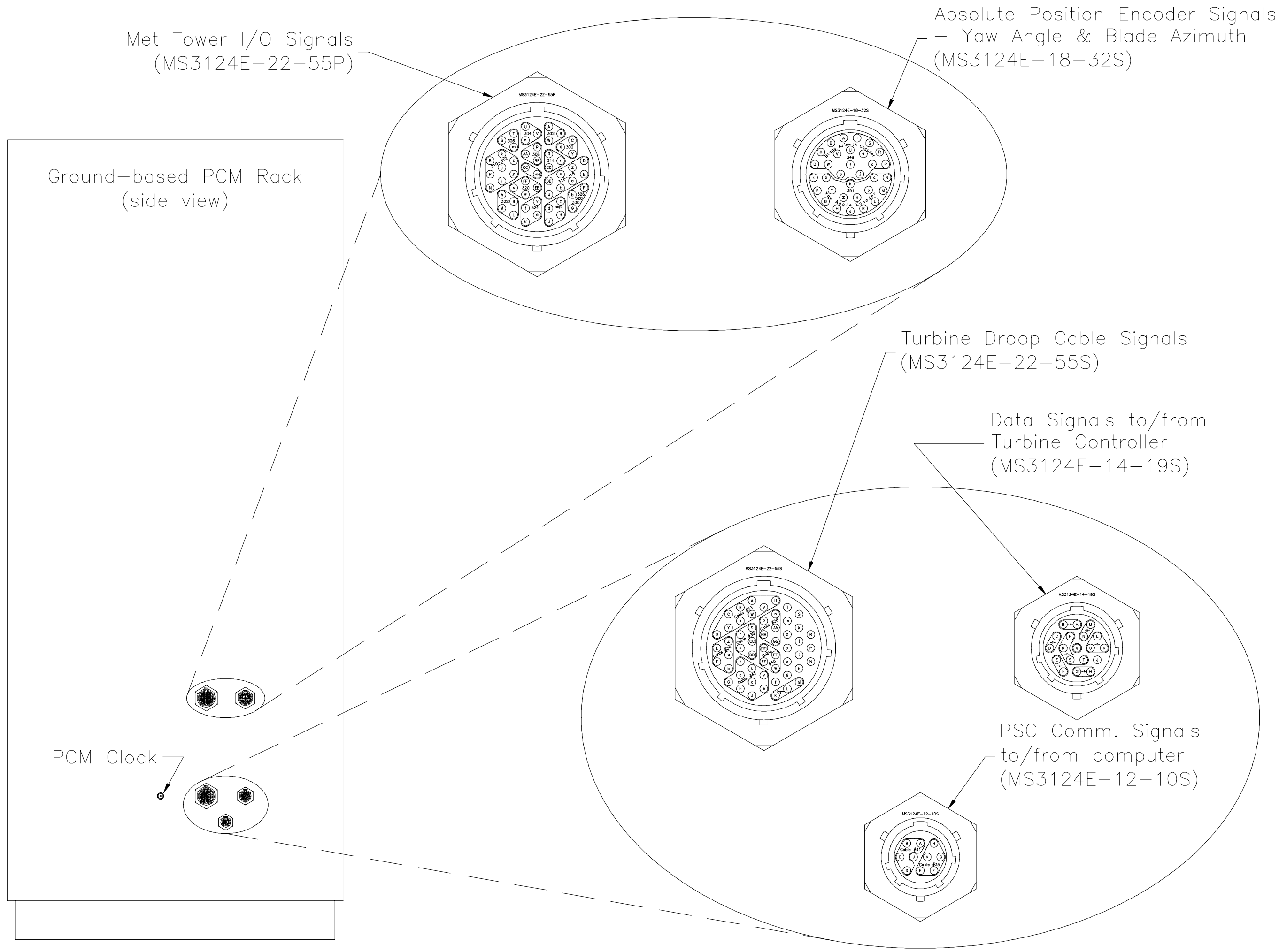


Figure F.11. Aspirator Alarm Panel Schematic

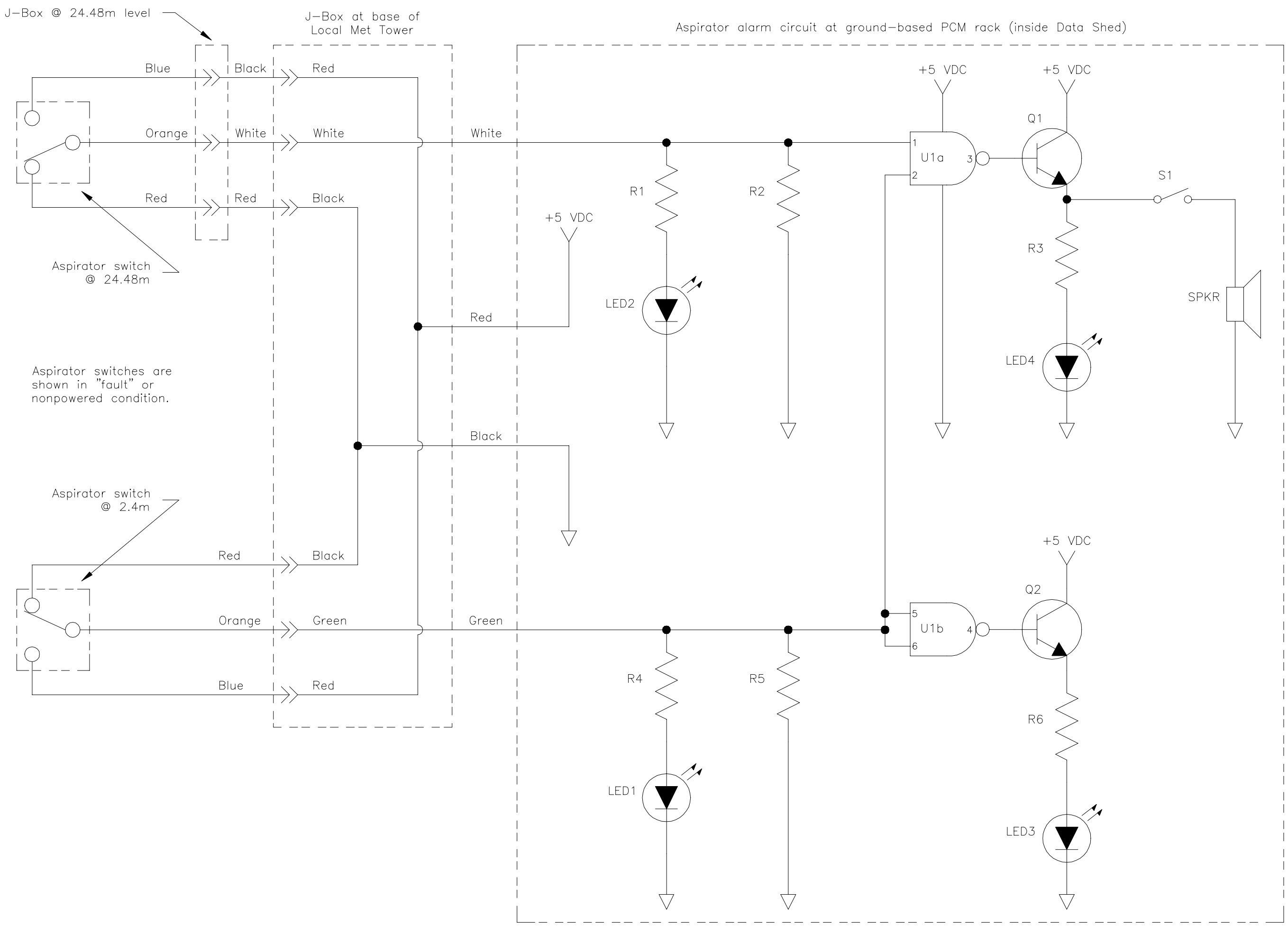
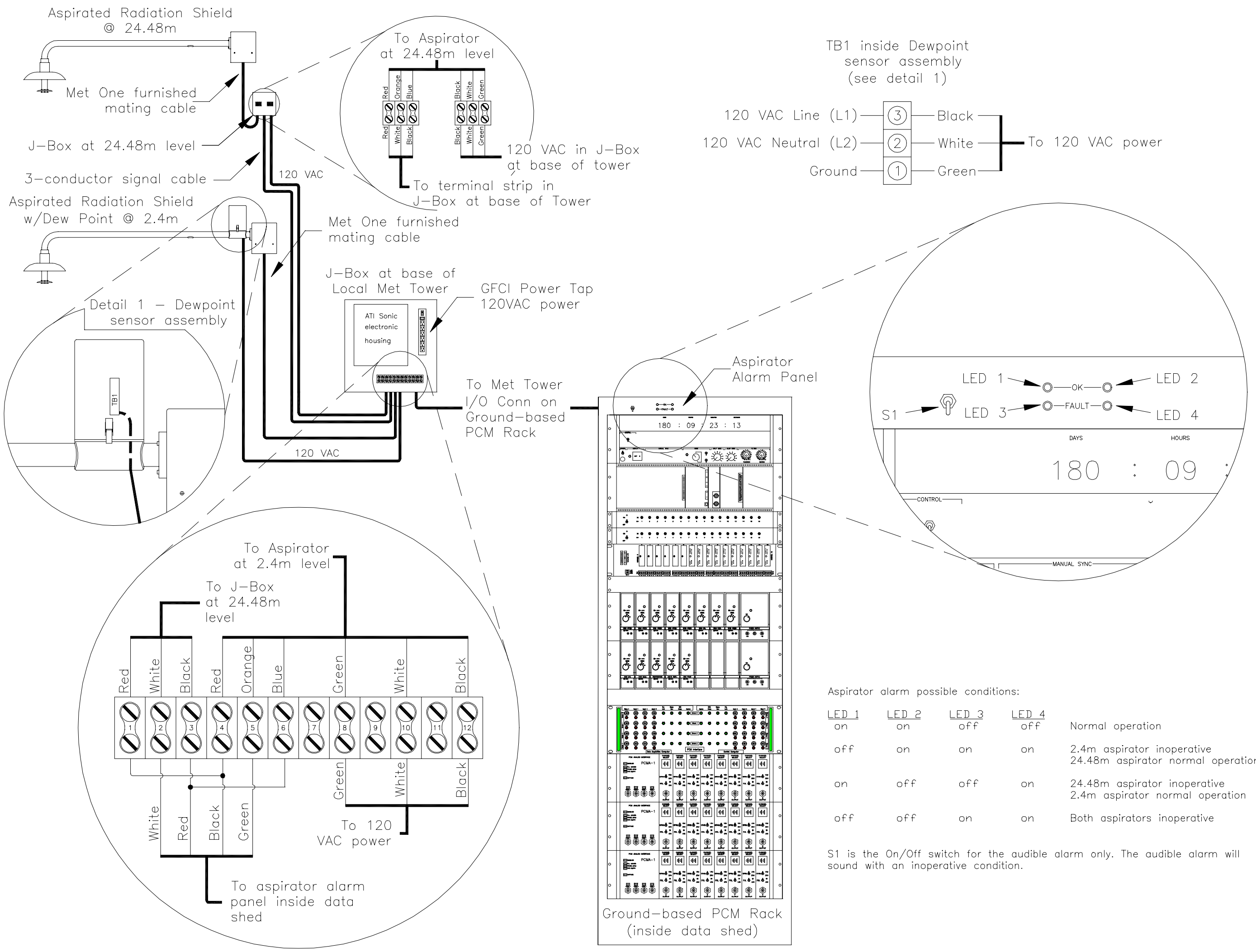


Figure F.12. Aspirator Alarm Panel Wiring

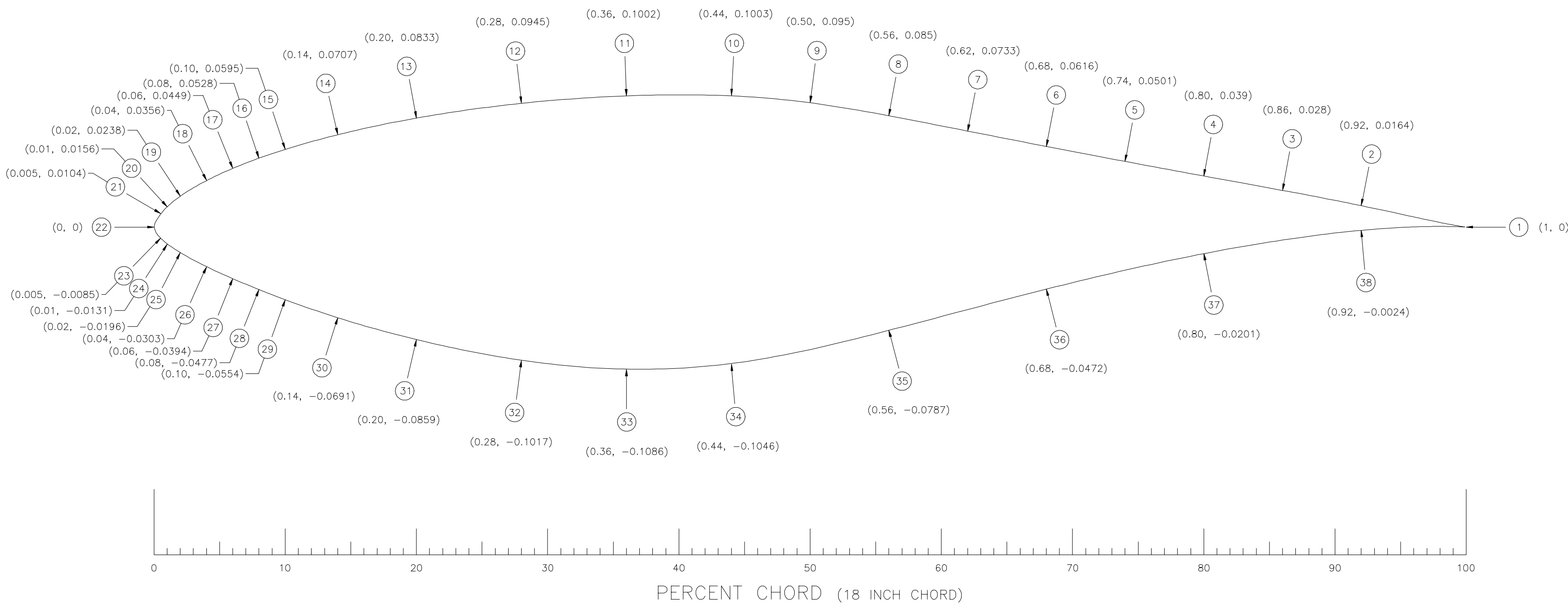


Aspirator alarm possible conditions:

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 F.13. Pressure Tap Layout



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NOTES

NOTES

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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 aerodynamic behavior of horizontal axis wind turbines. 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 earlier 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 Phases II - IV of the experiment is contained in this report.

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