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An Advanced Data-Acquisition System for Wind Energy Projects

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Abstract

NREL has subcontracted with Zond Systems, Inc. to develop an advanced data-acquisition system (ADAS) for wind energy projects. The ADAS can be used to simplify the process of making accurate measurements and analyzing data from wind turbines and meteorological towers. The system utilizes state-of-the-art electronics and telemetry to provide distributed multi-source, multi-channel data acquisition. Local stand-alone microprocessor-based data acquisition modules (DAMs) can be located near sources of measurement. These allow analog data values to be digitized close to the measurement source, thus eliminating the need for long data runs and slip rings. Signals from digital sensors and transducers can also be directly input to the local DAMs. A PC-based ground station is used to coordinate data transmission to and from all remote DAMs, display real-time values, archive data sets, and process and analyze results. The system is capable of acquiring synchronized time-series data from sensors and transducers under a variety of test configurations in an operational wind-park environment. Data acquisition needs of the wind industry differ significantly from those of most other technologies. Most conventional system designs do not handle data coming from multiple distributed sources, nor do they provide telemetry or the ability to mesh multiple incoming digital data streams. This paper describes the capabilities of the ADAS, and how its design and cost objectives are geared to meet anticipated US wind industry needs.

Introduction

There has been a significant increase in the need for measurement systems that can provide information necessary to further the development of wind turbine technology. NREL is currently involved in many cooperative projects with wind industry partners which explore new design concepts and evaluate their performance. Most of these projects require loads and performance testing of wind turbine systems and components. There are many data acquisition systems available which can be used to provide basic required measurements.

Obtaining measured values, however, is only a small part of the overall task. It is much more important and difficult to verify measured values to ensure data accuracy and reliability, and to use those values to produce results in a quick and efficient manner. This requires data acquisition hardware components which work in conjunction with data processing and analysis software. There are no existing systems which provide a complete package of hardware and software to meet the specific needs of the wind industry. NREL has initiated the development of the ADAS to meet these needs, and this paper describes existing capabilities in detail. Further system software developments are forthcoming as outlined in the Future Plans section below.

The ADAS specifications and required capabilities were defined by NREL's Wind Energy Program with input from the US wind industry. The hardware was designed and built by Zond Systems, Inc. under subcontract to NREL. Zond has operated wind farms and has instrumented and tested wind turbines since 1980. This system is based on an expanded version of previous systems designed, developed and manufactured by Zond (Cousineau, 1989). The hardware provides distributed multi-source, multi-channel field-experiment data-acquisition. It is capable of acquiring synchronized time-series data from wind turbines and meteorological towers in an operational wind-park environment under extreme environmental conditions. It utilizes cost-effective off-the-shelf components and equipment. It has the capability interface with data processing and analysis software to provide a basis on which to evolve to meet anticipated future wind industry needs.

Objective

The objective of the ADAS is to simplify the process of making accurate measurements and analyzing data from wind turbines and meteorological towers. The system will use state-of-the-art electronics, telemetry, and software to provide distributed multi-source, multi-channel data acquisition and processing for wind energy projects. The ADAS will:

- Provide a cost-effective data acquisition system that meets the needs of the US wind industry.
- Decrease the time and effort required to instrument a field experiment, verify data validity, collect data, and do preliminary data analysis.
- Improve the end-to-end accuracy of data collected in field experiments.
- Provide a versatile system capable of making a wide variety of reliable measurements in rugged environments using equipment of unobtrusive size and minimal weight.
- Provide stand-alone operation by utilizing telemetry and batteries which can be recharged on site.
- Provide a complete integrated package using off-the-shelf components, thereby minimizing custom electronics design, system integration, and software support and development functions.
- Develop flexible, expandable hardware that can be integrated with common experiment control software to provide necessary quick-look data display, processing, and analysis capabilities.
- Provide an easy way to get experimental data into a standard PC data file format, thus enabling users of varied computer skill and experience levels to use any inexpensive standard PC-based software products to perform post-processing analyses and displays.

Background

The ADAS was designed to provide synchronized time-series data from all measurement sources. This means that data values are measured on all channels exactly at time T. At an exact time interval Δt later (e.g., if the sample rate was 40 Hz, Δt would be .025 seconds), data values on all channels are measured again, and so on. This measurement accuracy is necessary to minimize sample phase and skew effects. A typical application, for example, might require structural dynamic studies and load-path evaluations using data from multiple sensors mounted in various positions on a structure.

Taking the ADAS objectives into consideration, a survey of available hardware showed that the required multiple-channels, multiple-source synchronized measurements could be performed in either the real-time or stand-alone mode. In the real-time mode, all data channels are synchronously sampled, and data is continuously streamed from many potential remote locations to a central receiving station. A computer at the central receiving station receives, combines, and stores the multiple stream data in real-time. This option becomes expensive as sample rates and number of channels increase because higher communication bandwidth and greater real-time computer processing and storage capability are required.

In the stand-alone mode, all data channels are synchronously sampled, and data values are recorded directly into the computer memory of microprocessor-controlled remote modules. Data sets are downloaded, combined, and stored on a central receiving station computer at a later time. This option eliminates the need for high-bandwidth communication links and computing requirements because data downloading does not have to occur in real-time.

NREL has traditionally operated data acquisition experiments in the real-time mode. High-bandwidth applications (>100 Hz) have been performed using pulse code modulation (PCM)-based telemetry systems designed for military and aerospace applications (Simms and Butterfield, 1990). These types of systems are not practical for the ADAS because high-bandwidth telemetry equipment is not commercially available and costs are prohibitively expensive for wind industry applications.

In other experiments, NREL has used typical personal computer (PC)-based data acquisition systems to provide real-time measurement capability (Tangler, et al., 1989). These systems are extremely cost-effective, but they require all analog signals to be conducted directly to the PC data acquisition boards. Since PCs are not rugged enough to use in most field applications, they have to be located in suitable environments to which measurement signal cables have to be run. These systems do not meet the objectives of the ADAS because they are difficult to install and debug on wind turbines, especially for measurements made on the rotor. Analog signals conducted over long distances are susceptible to induced noise from ground loops, high power sources, and slip rings. This affects measurement reliability and sacrifices accuracy.

The ADAS compensates for the expense of high-rate digital systems and unreliable analog systems by combining both the real-time and stand-alone modes of operation. The real-time mode is utilized for low data rates. In this mode, the ground station continuously triggers, polls, downloads, and displays results, completing a cycle from all remote stations in less than 1 second. This allows real-time monitoring on a visual display of current conditions which vary at an acceptable rate compatible with a human interface. This rate is suitable for performing most required visual data checks and verifications and can be accomplished using inexpensive common communication technology.

The stand-alone mode is utilized to obtain higher rate data sets by triggering all channels at all remote locations to start data acquisition at the exact same time. The real-time data values are streamed to internal memory on each microprocessor-controlled remote data acquisition module. At the end of a given period of data acquisition, data is then downloaded. The ground station computer polls each remote site individually to initiate transmission of its data. The data from each remote site are sequentially collected at the ground station and then assembled into a single time-series data set.

The advantages of stand-alone operation which contribute to the cost-effectiveness of the ADAS are:

- Low-cost radio-frequency (RF) telemetry is practical since all data transmission can be done on the same RF system. The need for multiple frequencies and multiple ground station transceivers is eliminated.
- A high-rate mode of digital transmission (e.g., PCM) is not needed. Lower-rate PC-compatible serial communication (e.g., RS-232, RS-422) can be used.
- Incoming data streams do not have to be multiplexed in real-time.
- Full duplex communication (transmission occurring simultaneously in both directions) is not required.
- Digital data are in standard PC-compatible format (ASCII), and do not require special decommutation hardware.
- A statistical summary characterizing the dataset in the remote memory can be downloaded and used to determine whether or not the entire time series is needed. This lends itself to automated test-matrix filling.

The disadvantages are:

- High-rate data cannot be continuously streamed and therefore contiguous long-period records cannot be saved and unexpected transients may be missed.
- Current conditions cannot be monitored while data from remote modules are being downloaded.
- The user may have to wait long periods between events while data is being downloaded, which may slow down experiment tasks.

ADAS Description

The ADAS is defined as a complete signal conditioning, data acquisition, and data processing package composed of both hardware and software components. Each ADAS package is made up of a single **Ground Station**, and one or many **Data Acquisition Modules (DAMs)**. A variety of different types of **Sensors and Transducers** may be connected to the DAM's **Signal Conditioning Cards**. Up to eight cards may be installed in each DAM. These filter and digitize analog signals from the sensors and transducers, directly input digital signals, and provide data to the DAM's master processor. Each DAM has a single 68332 microprocessor which controls data acquisition and communication functions. DAM to ground station interface is provided via a **Communication Link**. The ground station utilizes **Control and Processing Software** to perform required functions. A sample six-DAM data acquisition scenario is shown in Figure 1. Individual components of the ADAS system are further described and specified below.

Sensors and Transducers

The ADAS works with a wide variety of sensors and transducers, and allows them to be easily connected to the DAMs. The sensors and transducers produce some form of digital or analog output signal that usually varies linearly corresponding to changes in the measured parameter. Sensors and transducers vary widely and are extremely dependent on the nature of specific tests being conducted. Types of sensors and transducers typically used in wind turbine experiments are:

- Strain gage bridges.
- Strain gage bridge-based transducers, such as pressure transducers or accelerometers.
- Linear voltage output transducers ±100 mV to ±10 V.
- Anemometers, DC, AC or pulse output type.
- Wind vanes and other potentiometer or LVDT-based devices.
- Optical-type rotary encoders.

Data Acquisition Modules (DAMs)

These are located near the source of measurement to which transducer inputs are connected. They can be mounted at various locations including on the hub of a rotating wind turbine, on the wind turbine tower or in the nacelle, on a meteorological tower, in a turbine controller, or other such locations. This enables analog data signals to be digitized as close as possible to the measurement source to minimize noise induced by long signal paths. Many DAMs may be used concurrently. The DAMs may be exposed to harsh environments and are of robust design. Environmental specifications are shown in Table 1. They are capable of being battery-powered or AC/DC powered. The DAMs are able to accept, condition, and sample various types of analog and digital input signals from up to eight connected sensors and transducers.

Table 1. Data Acquisition Module Physical and Environmental Specifications

Size	16.3 x 20.3 x 28.9 cm (7.25 x 9 x 12.8 in) diecast aluminum enclosure. Easily mounted on or in another enclosure or structure.
Temperature	-25° to 85°C (-13° to 185°F) operating
Environment	Sealed, rain-proof enclosure, 0 to 100% humidity including condensing atmosphere.
Weight	(With eight analog input signal conditioners and mating connectors) Less than 9 Kg (20 lbs), excluding battery
Mounting	Internal and external mounting holes provided with enclosure.
Connections	Easy to connect/disconnect standard connectors from input signal cables, battery packs, and communications.
Channel signal conditioners	Easily interchangeable signal conditioning cards to provide for three types of signal inputs: either low-or high-level analog; digital; and high-speed pulse counting/anemometry.
Battery Operation	12 ampere hour battery system. Continuous operation duration can be extended using photovoltaic panels or DC power supply charging.
Battery Changing	Easily accessible and interchangeable batteries; battery change should take less than 5 minutes.

Each DAM has eight slots which can hold any combination of the following types of signal conditioning cards.

- High/low level analog card including excitation voltages.
- Pulse counting card
- Digital input card.

The analog signal conditioning cards provide excitation voltages, apply analog anti-alias filtering, and perform analog-to-digital (A/D) conversion. They can be configured to accept either high- or low-level voltage signals. Analog signal inputs are converted to digital format at true 12-bit (1 part in 4096) digital resolution with an integration period of 3.125 msec. The cards provide anti-alias filtering via 6-pole Butterworth anti-alias low-pass filters. These filters have programmable cutoff frequencies of 20 and 40 Hz which are practical levels for typical applications. In order to achieve required accuracy, the filters were designed to attenuate all input frequencies greater than the filter setpoint to a level less than one least significant bit of the A/D converter range. The analog cards also provide ground-station selectable gain levels of 1, 2, 10, 20, 100, 200 or 400. This corresponds to full-scale analog measurement ranges of ±10V, ±5V, ±1V, ±.5V, ±.1V, ±.05V, and ±.025V. The maximum accuracy obtainable with a gain of 400 is 12.2 micro-volts. The cards also provide excitation voltage levels of 1, 2, 4, 5, 6, 7, 9 and 10 VDC with ±.5 mV accuracy. This represents an error of less than 1 part in 4096 over a temperature range of -25° to +85°C. Analog card specifications are summarized in Table 2.

Pulse counting cards are typically used with pulse-generating anemometers and other types of pulse-emitting devices such as incremental encoders. The digital input cards accept digital status signals (on-off) or up to 12 bits of digital data, such as from a binary or gray-code transducer. Specifications for these cards are shown in Tables 3 and 4.

Table 2. Analog Signal Conditioning Cards

Analog Inputs	Differential or single-ended. Inverting and non-inverting.
A/D Converter	True 12-bit integrating type, integration period = 3.125 ms.
Sample Rate	160 Hz fixed, DAM digitally-averages values to produce lower rates
Input Overvoltage Protection	±100V
Bipolar Voltage Range	±10, ±5, ±1, ±.5, ±.1, ±.05, ±.025 V
Overall Channel Accuracy	±.025% FS typical, ±.04% FS max at ±10, ±5 V range ±.03% FS typical, ±.06% FS max at ±1, ±.5 V range ±.05% FS typical, ±.12% FS max at ±.1 V range ±.1% FS typical, ±.24% FS max at ±.05, ±.025 V range
Anti-alias Filter	6-pole Butterworth
Cutoff Frequency	20 or 40 Hz (-3db), or filter disabled
System AC Bandwidth	DC to 20 or DC to 40 Hz (-3db)
Excitation Driver	100 milliamperes current limited, sense and force leads separate.

Table 3. Pulse Counting Signal Conditioning Cards

Type of Pulse	AC (zero crossing wave form) or pulse output (square waves)
AC input frequency range	0 to 1500 Hz.
Pulse input frequency range	0 to 4000 Hz.
LED excitation	2.5, 5, 10, and 12 V
LED current limit	40 ma max (short-circuit-proof)
Transient and over-voltage	Included
Signal Filtering for AC input	Provided
Pulse Input Logic	HTL

Table 4. Digital Input Signal Conditioning Cards

Input Voltage Range	10 to 40 VDC
Number of optically isolated channels per board	12
Number of accumulators available	12
Maximum accumulation in counts	65,536
Maximum count frequency	8 Hz
Running sample rate (to master processor)	160 Hz
Isolation voltage	250 VDC

Each DAM can be controlled from the ground station. Control means selecting various options which affect the operational characteristics of the DAMs, and the interfacing between the DAMs and the ground station. DAM operations which can be ground-station controlled include:

- Type of operation: stand-alone or real-time
- Channel type (analog, digital, or pulse) and number of channels used
- Sample rate
- Low-pass filter setpoint
- Amplification
- Excitation voltage
- Synchronize and initiate data acquisition
- Initiate data download
- Calibrate

Each DAM samples data from up to eight incoming channels simultaneously. The number of operational channels which send data is selected and controlled from the ground station. A common system-wide sample rate can be selected from the ground station at various levels up to a maximum of 160 Hz. The DAM microprocessor provides slower-rate acquisition by digitally averaging the 160 Hz data samples in real-time to produce data at 80, 40, 32, 20, 10, 8, 5, 4, 2 and 1 Hz. For sample rates below 1 Hz, long term averages of 2, 5, 10, 30 seconds, and 1, 2, 5, and 10 minute periods are available. By using separate A/D converters on each channel, all channels on each DAM are sampled simultaneously to eliminate skew or inter-channel phase-shift effects. All DAMs are simultaneously triggered to start acquisition (within 400 nano-seconds) from the ground station.

Each DAM comes with 1 Mbyte of standard user-available memory. This is expandable to 4 Mbytes by installing plug-in memory modules. The technology used is low-power static RAM. The available recording space varies depending upon the number of channels and the sample rate. At a 20 Hz sample rate and eight channels, a 54.6 minute time series data record can be recorded into 1 Mbyte of RAM. With a full complement of RAM, this time increases to 3.64 hours. Acquisition duration for various combinations of sample rates and memory are shown in Table 5. The memory can be used to hold a single contiguous time series up to the maximum duration shown in Table 5, or any number of shorter-duration segments. Acquisition duration for DAMs operating at 1 Hz or less is limited only by the amount of available hard disk space, since real-time acquisition direct to PC data files occurs at these rates.

Table 5. Data Acquisition Duration

Rate (Hz)	Channels	Duration for 1 Mbyte RAM	Duration for 4 Mbytes RAM	Rate (Hz)	Channels	Duration for 1 Mbyte RAM	Duration for 4 Mbytes RAM
10	1	14.6 hrs	2.43 days	80	1	1.82 hrs	7.28 hrs
10	4	3.64 hrs	14.6 hrs	80	4	27.3 min	1.82 hrs
10	8	1.82 hrs	7.28 hrs	80	8	13.7 min	54.6 min
40	1	3.64 hrs	14.6 hrs	160	1	54.6 min	3.64 hrs
40	4	54.6 min	3.64 hrs	160	4	13.7 min	54.6 min
40	8	27.3 min	1.82 hrs	160	8	6.83 min	27.3 min

Each DAM can be operated with either an AC line power (120, 240 or 480 VAC), DC power supply, or a DC battery pack. Each battery pack can be recharged with the same AC line power supply or by using standard photovoltaic panels. At an ambient temperature of 25°C, each DAM can operate continuously for 20 hours if configured for eight full strain-gage bridges with 350 ohm gages excited at five volts DC, and communications via the RS-232 port. At 0°C, this will drop to less than 12 hours. Recharge time is six to eight hours for a fully discharged battery pack.

Communication Links

Communication links are used to provide two-way communication between DAMs and a ground station. Asynchronous serial communication is used throughout. The DAMs are able to download their digital-format data by transmitting it using RF telemetry, or conducting it through an interconnecting cable to the ground station. They are also be capable of being controlled and configured by ground station commands uploaded over the same cable or RF link. Both RS-232C and RS-422 are available. RS-232C can be used for short communication distances up to 24 m (80 feet) from a single DAM through a direct-connect cable with a maximum baud rate of 115,200. RS-422 is used for multiple direct-connected DAMs at greater distances, up to 1000 meters (3281 ft) at 19,200 baud, and up to 2000 meters (1.24 miles) at 9600 baud. Of more importance is the optical isolation provided by these devices. Such isolation solves any ground loop problems that may come about when using AC power.

RS-232C interfaced radio links are also available for DAM communication. These eliminate the need to run a cable from the DAM to the ground station. Multiple RF links can be used, one at the ground station, and one at each DAM. Each is capable of both transmitting and receiving. The RF links provide communication at 19,200 baud up to 4570 m (2.8 miles). They utilize spread spectrum technology (which uses several frequencies across a broad band from 902 to 920 MHz), are inexpensive, are authorized by the FCC, and require no license. Download rate depends on the distance the DAMs are located from the ground station and the type of communication link. Data download duration options are shown in Table 6. Data cannot be downloaded from more than 1 DAM at a time; therefore rates are cumulative for multiple DAMs.

Table 6. Data Acquisition Module Download Rates

Communication Type	Data Rate (Baud)	Distance (m)	Duration for 100 Kbytes RAM	Duration for 1 Mbyte RAM	Duration for 4 Mbytes RAM
RS-232C Direct Connect	115200	<3	10 sec	1.7 min	6.7 min
RS-232C Direct Connect	19200	<24	60 sec	5 min	20 min
RS-232C RF-link	19200	<4570	60 sec	5 min	20 min
RS-422 Direct Connect	19200	<1000	60 sec	5 min	20 min
RS-422 Direct Connect	9600	1000-2000	2 min	10 min	40 min

Ground Station

The ground station receives and stores incoming data, and it originates DAM control commands. It also runs software to present a user-friendly interface to control the DAMs, and produce data in a format easily used by standard PC DOS-based system software. The ground station is typically located at a convenient central site such as a test shed or trailer. It can be any PC-compatible computer and does not require custom hardware or modifications. It has the ability to communicate with up to 16 DAMs using a standard internal RS-232 to RS-422 converter board. It can be configured with typical memory and hard disk capacities to suit anticipated data volumes and analysis software requirements. Standard DOS-compatible devices such as tape backup units or optical disk drives can be used to provide permanent data archive.

Three basic software functions are provided with the ADAS system to run on the ground station. The first function enables the operator to configure channels on each DAM as described above. The second allows data to be downloaded from each DAM and stored to PC hard disk or RAM (in binary format). This software also provides the ability to convert the stored data to engineering units by applying linear conversion factors, combine data from multiple DAMs into a single contiguous time series, and output binary or ASCII data files. A compatible header file is also produced along with the data sets to save operator field notes, data conversion factors, and other information. The third software function allows real-time alpha-numeric monitoring and display of current conditions in engineering units. The display refreshes at least the 1 Hz real-time rate reflecting the current status of all channels on all DAMs. Actual real-time display refresh rate capability varies widely, depending on the number of DAMs which compose a system. If a system consists of a single DAM with eight channels, real-time rates of 20 Hz are attainable. A maximum of 10 Hz is available with two DAMs operating a total of 16 channels, and a maximum of 1 Hz is available for eight DAMs operating 64 channels. A typical data path from transducer to ground station is depicted in Figure 2.

Future Plans

The hardware described is extremely flexible and capable of evolving to meet future anticipated data acquisition, display, and processing needs. Two areas of development are planned for the immediate future. First, work will continue on improving the download capabilities utilizing new technology communication links in an effort to decrease download time and increase real-time rates in a cost-effective way. The capability to operate the system so that high-rate acquisition data is transmitted to the DAM memory while low-rate (1 Hz) data is simultaneously downloaded in real time will be provided so that real-time monitoring of current acquisition status can be accomplished. Second, it is planned to specify and develop software tools needed to facilitate collection, display, calibration and analysis of multiple-source wind turbine test data. This will most likely involve interfacing the ADAS hardware with an existing third-party software package which can meet all required needs. Some desired options include:

- Real-time quick-look alphanumeric and graphical display of current measured and calculated parameters.
- Digital filtering, de-spiking, interpolation, fast fourier transform (FFT) for power spectra, rainflow counting, and other time-series and frequency-domain signal processing capabilities.
- Test matrix parameter definition and automated test matrix filling.
- Statistical data processing including standard deviation and higher order moments, curve fitting, linear and higher-order regression, especially for the purpose of calibrating transducers and calculating calibration coefficients.
- Parameter binning to provide blade azimuth averaging, wind roses, power curves, etc.
- Database capabilities for defining and maintaining information associated with all measured data channels, keeping track of channel configurations, parameters and histories, especially for organizing transducer calibration records and calculating measurement uncertainties.
- File maintenance system to organize and catalog experiment-associated data files and channel database records.
- Test event control and log to define a sequence of experiment events, initiate appropriate actions, and record results. Graphical utilities to provide comprehensive post-processing data display and presentation.
- Provide all capabilities through a common, easy-to-use, graphical user interface (e.g. Windows)

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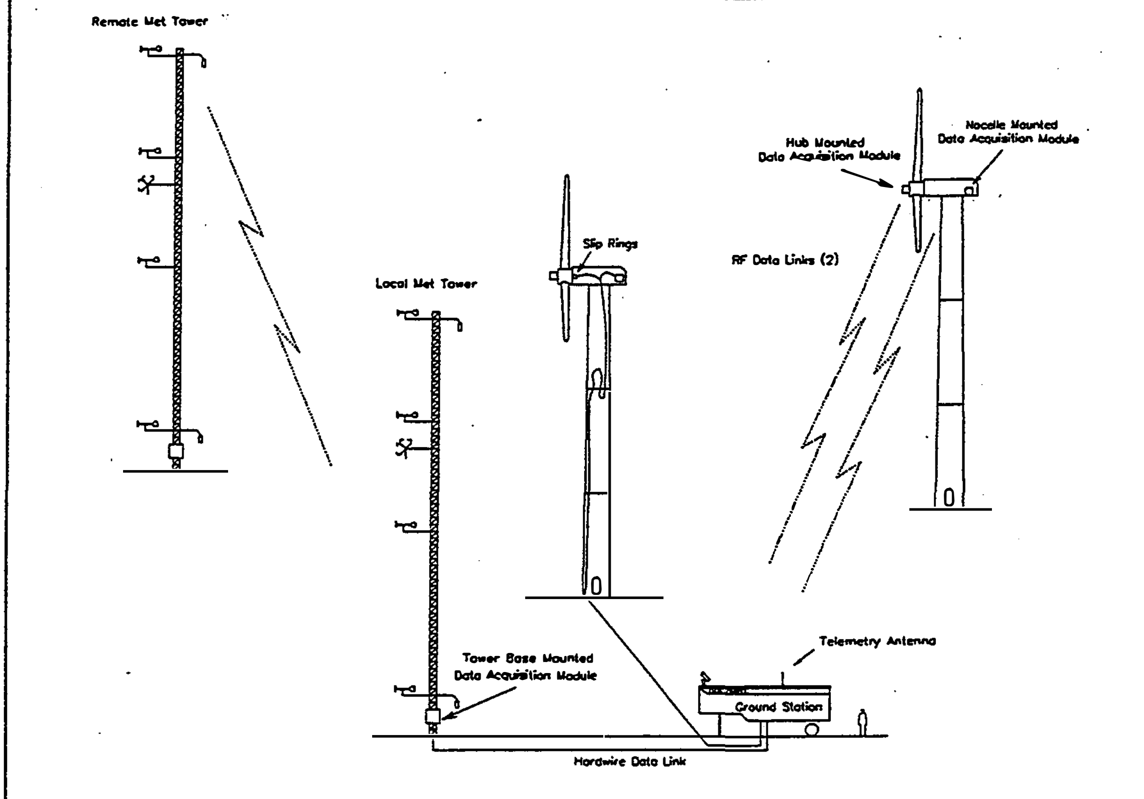

Figure 1 - Six-Module Scenario

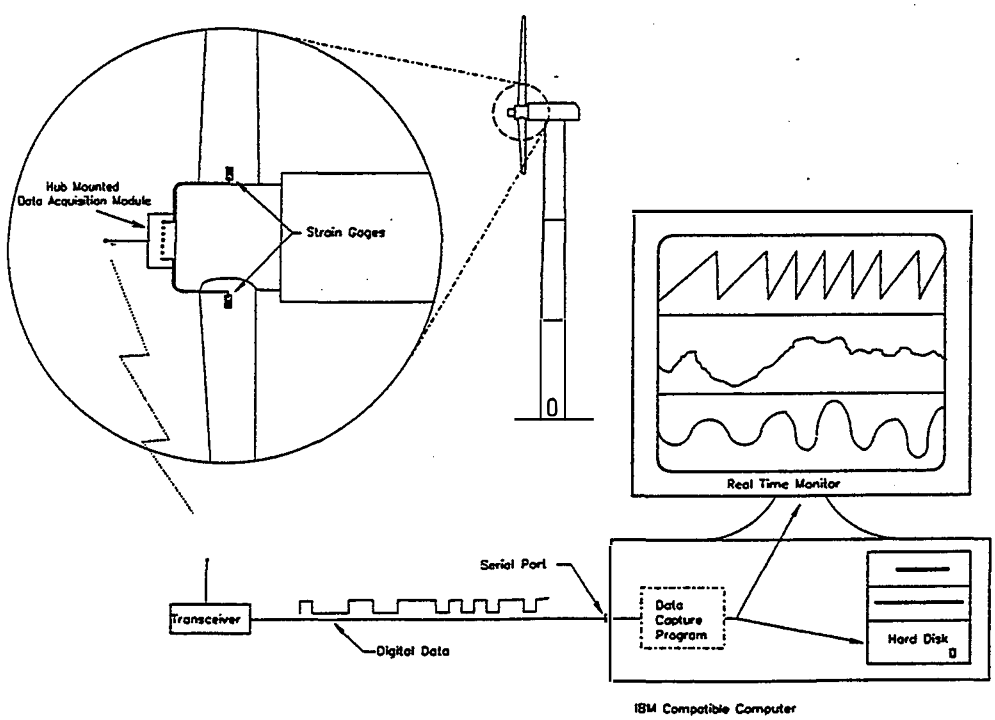

Figure 2 - Sample Data Path